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PHYSICS

The Amplifier-Oscillograph Applied to the Study of Dielectrics With Continuous Potentials

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The underlying causes of the losses occurring in dielectrics when subjected to alternating stress have long been a subject for speculation. There have been a number of proposals of methods for linking such losses with the dielectric behavior under continuous or d-c. electrical stress. To investigate the validity of the suggestions for correlating the d-c. properties of dielectrics with their a-c. losses, the continuous currents flowing must be measured as soon as possible after the d-c. voltage is applied to or removed from the specimen. The development of the amplifier-oscillograph permits a much improved and satisfactory technique. With the apparatus and method described here, observations could be begun within one or two thousandths of a second after the specimen had had the d-c. voltage applied, or had been short-circuited and they could be continued as long as desired. By this method, a connected series of observations was obtained with a single cycle of voltage application, removal, and short circuiting of the specimen, greatly expediting the work and eliminating inaccuracies arising from changes in the dielectric sample during the long periods of time heretofore required for such studies. The apparatus employed consisted principally of a quick acting, spring-actuated switch for operating the specimen circuits rapidly, and a sensitive-amplifier-oscillograph for recording the dielectric currents. On operating, the quick acting switch shunted the geometric charge of the specimen to ground for a brief interval after applying voltage to the specimen, or short-circuiting it, and then connected the amplifier-oscillograph to the measuring circuit. The observations could be continued as long as desired with a D'Arsonval galvanometer of high sensitivity. The amplifier-oscillograph attained a sensitivity of 1.6×10^{-8} ampere per mm deflection, which is about 300,000 times that of the oscillograph alone. The vacuum tube amplifier which accomplished this extension of range was in three stages, pure resistance coupled for the accurate reproduction of continuous currents. Many precautions were taken and tests made to ensure the reliability of this instrument and its connecting circuit apparatus.

INTRODUCTION

THE underlying causes of the losses occurring in dielectrics when subjected to alternating electric stress have long been a subject for speculation. There have been a number of proposals of methods for linking such losses with the dielectric behavior under continuous or d-c. electrical stress, notably that of von Schweidler[1] using the superposition theories of absorption of Hopkinson[2] and Curie[3] as a foundation. For liquid dielectrics, Tank[4] reported

[1] E. von Schweidler, Ann. d. Physik **24,** 711 (1907).
[2] J. Hopkinson, *Original Papers,* 2 Vols., Cambridge University Press, 1901.
[3] J. Curie, Ann. Chim. Phys., [6] **18,** 203 (1889).
[4] F. Tank, Ann. d. Physik **48,** 307 (1915).

an initial limiting value of the d-c. charging current as accounting for the a-c. losses in them. The various theories and related experimental evidence have been reviewed, compared, and discussed comprehensively by Whitehead.[5,6]

In a study of impregnated cable paper and its component parts made at the Johns Hopkins University, the relation of the a-c. losses to the behavior of the dielectrics under continuous electrical stress was investigated. A number of reports on this work have already been published.[7,8,9,10,11] The present paper gives a description of the methods and technique developed for making the d-c. measurements in this study. To investigate the validity of the suggestions for correlating the d-c. properties of dielectrics with their a-c. losses, the continuous currents flowing must be measured as soon as possible after the d-c. voltage is applied to or removed from the specimen. Until recently, the methods employed have for the most part been similar to that of Hopkinson[2] employing a form of Helmholtz pendulum. This was a point-by-point method, involving a great number of observations for each specimen, with a considerable lapse of time between them, and with resulting difficulties and inaccuracies entering from changes of specimen temperature and dielectric condition. Many experimenters have been content with much slower galvanometer methods, obtaining their initial readings within a matter of some seconds after voltage application or removal, instead of within a small fraction of a second as is desirable.

The development of the thermionic vacuum tube and electromagnetic oscillograph now permits a much improved and more satisfactory technique. Benedict[12] has described an adaptation of such equipment to studies of dielectrics. With the apparatus and methods described here, observations can be begun within one or two thousandths of a second of the d-c. voltage application or removal and can be continued as long as desired. By these methods, a connected series of observations may be obtained with one cycle of voltage application and removal, greatly expediting the work and eliminating possible inaccuracies due to changes in the dielectric sample during the long periods of time heretofore required for such studies.

Specimen Testing Conditions

The three classes of cable materials used in our work—compounds of oil, paper, and impregnated paper—were all made up into specimens having the same physical dimensions. Each had the form of a guarded concentric cylin-

[5] J. B. Whitehead, A.I.E.E. Trans. **45,** 102 (1926).

[6] J. B. Whitehead, *Lectures on Dielectric Theory and Insulation,* New York, McGraw-Hill, 1927.

[7] J. B. Whitehead, Journal Franklin Inst. **208,** 453 (1929).

[8] J. B. Whitehead, A.I.E.E. Trans. **50,** 692 (1931).

[9] J. B. Whitehead and W. B. Kouwenhoven, A.I.E.E. Trans. **50,** 699 (1931).

[10] J. B. Whitehead and A. Banos, Jr., *The Predetermination of the A-C. Characteristics of Dielectrics,* A.I.E.E. Winter Convention, 1932.

[11] J. B. Whitehead, Physics **2,** 82 (1932).

[12] R. R. Benedict, A.I.E.E. Trans. **49,** 739 (1930).

der condenser. The inner cylinder, or high voltage electrode, was 2.500 in. in diameter and 24 in. long. The outer cylinders, or low voltage electrodes, were 2.620 in. in diameter, made up into three sections. The measuring electrode was ten inches long, centrally located along the length of the high voltage electrode. The two guard electrodes at the ends of the measuring electrode were each three inches long, with a separation of one-sixteenth of an inch between them and the measuring electrode. These samples had an electrostatic capacity ranging from about 720 mmf for paper and oil separately to about 1200 mmf for impregnated paper.

The regular test voltages were 500, 1000, and 1500 volts d-c., but voltages as low as 200 volts d-c. have been used. The specimens have been mounted in testing tanks for maintaining them at constant temperatures ranging from 30 to 105°C. These tanks and their temperature regulating apparatus have already been described.[13]

Measurement Procedure

The same procedure was followed for studying the d-c. behavior of all three classes of dielectrics. An amplifier-oscillograph began recording the circuit current an instant before voltage was applied to the specimen undergoing investigation. This record could be continued for only one-twentieth of a second, or for as long as a minute and a half, depending upon what portion of the charging current curve was of primary interest in a given test. When this oscillographic record had been completed, the amplifier-oscillograph was replaced in the measuring circuit by a sensitive D'Arsonval type of galvanometer. With this instrument the charge currents could be measured for as long as desired, forty minutes being taken as an arbitrary standard period of observation in our studies.

The discharge currents were measured in the same manner, the oscillographic record beginning just before voltage was removed from the specimen and the specimen short circuited and grounded. This was then followed by observations with the high sensitivity galvanometer.

The Recording Apparatus

The three-stage, pure resistance coupled amplifier used to extend the range of the oscillograph for this work has been described in an earlier paper.[14] When operating within the normal range of the instrument, the grid potential of the input tube varied between -2.100 and -2.170 volts with respect to the negative end of the filament. This permitted a maximum net variation of 0.070 volts. Preparatory to making a measurement, the bias on the input grid was adjusted to its most favorable value for obtaining large deflections without extending beyond the normal operating range.

The measuring circuits were so arranged that the grid of the input tube became more negative with an increase in the d-c. charge current of the specimen. Therefore, when making charge records, the input bias was adjusted to

[13] W. B. Kouwenhoven and S. K. Waldorf, Elect. World **95,** 1214 (1930).

[14] S. K. Waldorf, Journal Franklin Institute **213,** 605 (1932).

its most positive value, −2.100 volts. As the grid became more positive upon the flow of a discharge current, its direction of flow being opposite to that of a charge current, the bias for these measurements was adjusted to its most negative value permissible, −2.170 volts. By adjusting the bias in this manner for each class of record, the zero position of the light spot on the oscillograph was shifted from one end of its operating range to the other, in order that its allowable travel could be utilized to the fullest extent.

For this work, the oscillograph was especially equipped to give film speeds varying over a wide range, from about seven inches per minute to about 20 ft. per second. For the slower speeds, the 120-volt film driving motor had its armature supplied from a 6-volt storage battery with full field excitation. This arrangement gave a steady slow speed drive superior in uniformity to that obtainable with the usual series resistance in the armature circuit. For the slowest speeds, the slow running motor drove a screw type of speed reducer.

The Specimen Circuits

In Fig. 1 are given the principal connections of the specimen circuits preparatory to recording a discharge current curve. The storage battery serv-

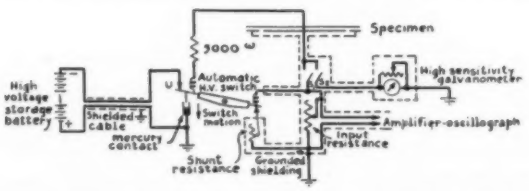

Fig. 1. Principal specimen circuit connections for obtaining discharge current curves. For recording charge currents, the only changes made were grounding the contact *U* and connecting the mercury contact to the high voltage.

ing as the high voltage source for testing had a range up to 1500 volts d-c. Due to the physical arrangement of the laboratory, this battery was about 150 ft. away from the testing apparatus. A two conductor lead-covered cable was used to effect the connection between them, and in order to avoid picking up disturbances on this cable from neighboring high voltage circuits, it was found necessary to ground its lead sheath.

The synchronization of the opening of the oscillograph shutter and the application or removal of voltage from the specimen was accomplished by means of a quick acting high voltage switch, actuated mechanically by a spring, and tripped electrically by the operation of the oscillograph shutter This switch, with the adjacent resistance boxes used as the amplifier input and shunt resistances, is shown in Fig. 2.

In the illustration, the light hard rubber arm carrying the movable contacts is shown in the set position sloping downward from left to right, preparatory to exposing a film. The arm was pivoted in the middle, so that on being tripped, the left end moved downward and the right end upward. By referring to Fig. 1, it can be seen that this motion opened the upper contact *U*, removing voltage from the specimen, and an instant later closed the mercury

contact to discharge the specimen with switch S_1 closed and S_2 open. On the right end of the moving arm was a contact which stayed closed for an adjustable predetermined period after the mercury contact closed. This contact shunted the geometric charge around the input resistance to relieve the amplifier-oscillograph for a brief interval. As it was necessary to know when the timing began on oscillograms, a shunt resistance of two one-ohm coils of a resistance box was used to produce a small deflection on oscillograms upon the passage of the geometric charge. The shunting period could be made to last over a period of time variable from 0.1 to 6 milliseconds. When the low voltage contact opened at the end of the shunting period, the specimen current flowed through the input resistance, causing a deflection on the amplifier-oscillograph and a record of the specimen current behavior to be traced on the oscillogram. The input resistance was adjusted to suit each set of testing conditions, with 100,000 ohms used to give the amplifier-oscillograph its maximum sensitivity of approximately 1.6×10^{-8} amperes per mm deflection. After completing an oscillogram, switch S_2 was closed and S_1 then opened to permit measurement of the residual currents with the high sensitivity

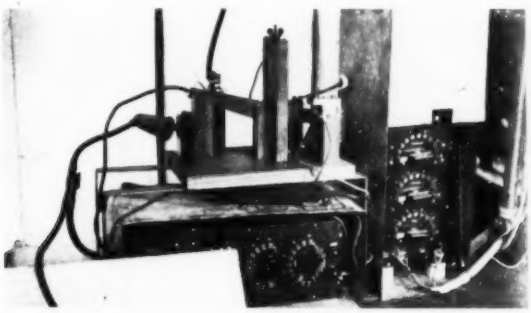

Fig. 2. The quick acting high voltage switch. The covers of the shielding boxes of the shunt and input resistances are shown partially removed.

galvanometer over relatively long periods of time. This galvanometer, as it was set up with a scale distance of three meters, had a sensitivity of 1.9×10^{-11} amperes per mm deflection. The high voltage circuits were so arranged that the automatic switch could be reset to be in readiness for obtaining discharge currents while still taking such long time readings of charge currents. The resetting operation was done without removing voltage from the specimen.

The mercury contact on the automatic switch is worthy of special attention, as it was the only one of a number of methods tried which gave the instantaneous, non-chattering contact essential for this type of work. It was made in the form of a pointed piece of No. 22 B and S gauge copper wire dipping into a small reservoir of mercury. The scum which formed on the exposed mercury surface when left standing for a while had to be removed before each test, but the mercury itself was used satisfactorily for several months without replacement. When not in use, the fine wire was kept clean by leaving it submerged in the mercury.

Elimination of Interference and Other Extraneous Effects

The most difficult problems to be solved were those arising from disturbances induced in the recording circuits from external sources. These sources of disturbance were primarily mechanical vibrations due to operation of machines in the laboratory, the operation of high voltage circuits, both in testing circuits of this research and other nearby researches, the functioning of the necessary trip and control circuits of this research equipment, and very slight and erratic voltage unsteadiness in the high voltage storage battery.

Difficulties due to mechanical vibrations were removed by stopping offending machinery as far as possible during measurements, and by mounting the entire amplifier unit, batteries, table, and all on sponge rubber. At times the mechanical vibration of the specimen condensers alone, although hardly sensible to an observer, would be sufficient to produce irregularities on oscillograms.

To eliminate interference from neighboring high voltage circuits and from that of this apparatus, the high voltage circuit of this apparatus was surrounded with grounded shielding except at disconnecting switches, the automatic switch, and the high voltage battery itself. In addition to this, the control and measuring circuits were all completely shielded from outside circuits and from one another. All measuring circuits were insulated with high quality insulation, either Bakelite or porcelain, paraffine coated, or with solid blocks of paraffine. The shielded trip circuit from the oscillograph shutter to the automatic switch was supplied from a six-volt storage battery and the trip coil was fitted with a parallel discharge resistance.

The 5000-ohm lavite resistor shown in the high voltage lead of the specimen in Fig. 1, and a 0.5 megohm resistor in the lead to the input grid of the amplifier were found essential to dampen out troublesome transients set up by the initial current impulses resulting from charging or discharging specimens. The resistor in the grid lead also served to suppress interference from neighboring high voltage circuits in the laboratory.

Occasional defective contacts developed in the high voltage storage battery. They caused minute voltage unsteadiness, undetectable with a high range d-c. voltmeter, yet producing defective oscillograms. The remedy here obviously was the isolation and correction of the poor contacts.

Tests of Reproduction

Several tests of accuracy of recording of the amplifier-oscillograph were described in earlier papers.[14,15] A number of additional tests have been made, giving special consideration to the character of variation of dielectric currents.

Fig. 3 shows the characteristic response of the instrument to interrupted d-c. currents. The rounding of the wave front has been shown by test to be characteristic of the oscillograph vibrator alone, due to its overdamped behavior in operation. The final steady deflection is reached within two or three

[15] S. K. Waldorf, A.I.E.E. Trans. **47**, 1418 (1928).

milliseconds after the current change. This test of reproduction is of value when studying the limitations of the method as applied to cable oils, as can be seen by comparison of Fig. 3 and the top record of Fig. 6. The latter record is a charge current record of such an oil and has the characteristic rounded wave

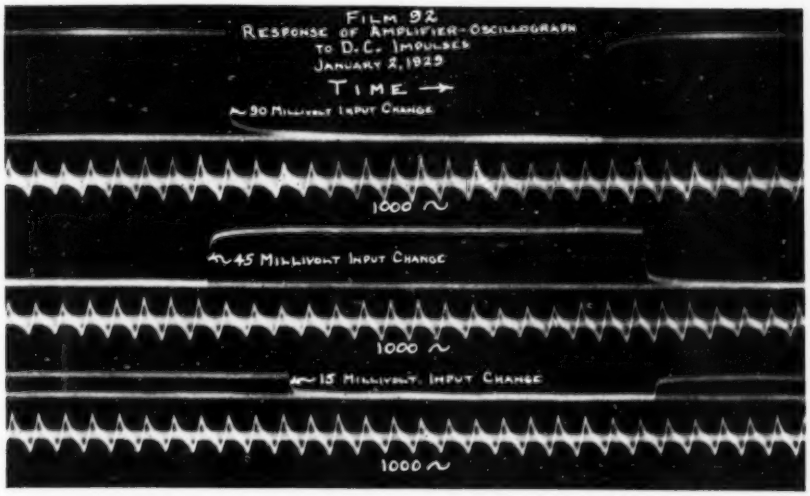

Fig. 3. Reproduction of rectangular wave by the amplifier-oscillograph. Note the characteristic rounding of the wave front by the oscillograph vibrator.

front. The comparison indicates that the gradual increase in deflection when recording the charge current is not due to a gradual increase in the specimen current during the first millisecond or so, but to lag in the vibrator.

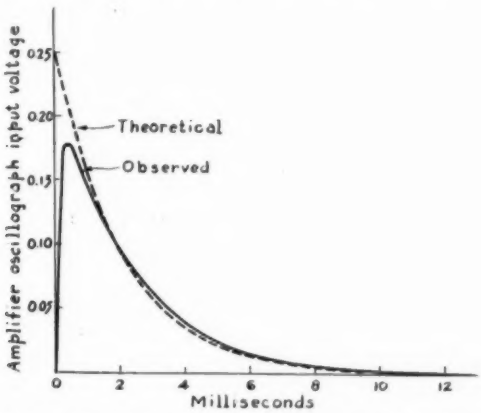

Fig. 4. Check of amplifier-oscillograph accuracy. The input of the instrument was connected to the terminals of a 1μf mica condenser discharging through 2000 ohms.

Fig. 4 is the result of an investigation of the instrument's accuracy with a current variation very similar to that obtained on charging or discharging a highly absorptive specimen. The observed curve agrees very closely with that calculated from the circuit constants.

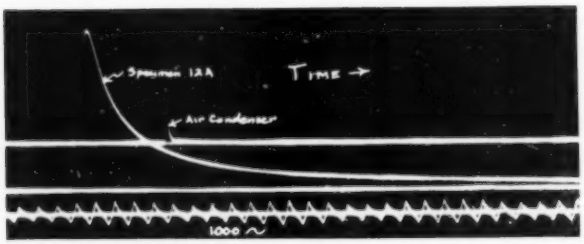

Fig. 5. Typical discharge current records at 1500 volts. Specimen 12*A* was an impregnated cable paper specimen and the air condenser was of the same capacity as the specimen.

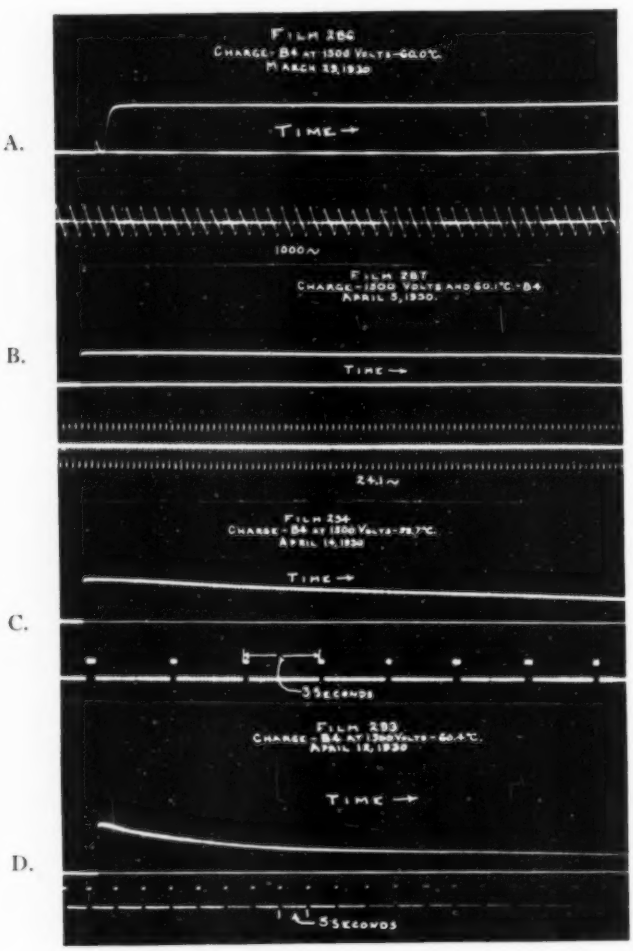

Fig. 6. Typical charge current records of a cable oil with different film speeds. Duration of records: *A*—36 millisec. (0.036 sec.); *B*—4 sec.; *C*—23 sec.; *D*—93 sec.

Fig. 5 showing the discharge currents of an impregnated cable paper specimen and of an air condenser of equal capacities, is the result of a test to show that the recorded discharge current of the specimen is purely that due to absorbtion effects and not due to geometric charge. This is proved by the discharge current of the air condenser, which is free of absorption, lasting for only the shunting period of the automatic switch. The recorded residual current of the specimen, being of the same capacity, must therefore, be that due only to absorbed charge.

Typical Oscillograms

Fig. 5 is typical of charge and discharge currents of impregnated paper and of air condensers under study.

Fig. 6 is a group of records of the charge current of a sample of cable impregnating oil taken under fixed conditions of test, but with different film speeds varying over the range used in this work. Under the given condition of specimen temperature, there was no discharge current detectable with the amplifier-oscillograph, although the high sensitivity galvanometer indicated an exceedingly minute amount flowing for as long as twenty minutes after discharge began. Record *A* of Fig. 6 brings out nicely the efficacy of the shunt resistance (Fig. 1) in indicating the instant of the application of voltage to the specimen.

The earliest moment at which a reasonably dependable reading could be obtained with the high sensitivity galvanometer was at about one minute after the application of voltage to the specimen. The records of Fig. 6 show the flexibility of the amplifier-oscillograph as used, and how it permitted a complete history of the variation of dielectric currents to be obtained in the interval before the ordinary type of galvanometer becomes effective.

Acknowledgment

The author wishes to acknowledge his indebtedness to the Utilities Research Commission of Illinois which gave financial support to the studies for which this development was made, and to Doctor J. B. Whitehead, who supervised and directed the studies.

Summary

The amplifier-oscillograph as applied to the studies of dielectric behavior has several outstanding features and advantages:

1. The flexibility, simplicity, and ease of operation of the recording apparatus as embodied in modern forms of electromagnetic oscillographs.

2. A complete and connected series of charge and discharge current observations is obtainable with only one cycle of application and removal of specimen voltage.

3. Dependable current measurements can be made beginning at about one and a half to two milliseconds (1.5×10^{-3} sec.) of the application or removal of voltage. With intervals of time much shorter than this, an appreciable loss of precision in current measurement results from the inherent lag of oscillograph vibrators.

4. The timing of switching operations is readily adjustable and is measurable on the oscillograms to within 5×10^{-5} sec.

5. In most cases, the current measurements can be continued as long as desired with a D'Arsonval galvanometer of high sensitivity.

6. The amplifier-oscillograph attains for this work a sensitivity of 1.6×10^{-8} amperes per mm deflection with an input resistance of 10^5 ohms as a maximum value. Further increase in sensitivity above this value is limited by inductive disturbances from the high voltages necessary in dielectric study. The sensitivity is now about 300,000 times that of the oscillograph alone.

A New Low Noise Vacuum Tube

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(Received May 23, 1932)

When commercial vacuum tubes are used to amplify small low-frequency voltages it is found that random disturbances of the order of 100 to 1000 microvolts are present in the anode circuit. These disturbances exist almost entirely in the range below 100 cycles per second, and therefore fix the minimum voltage which can be measured over this low frequency band from 10 to 100 microvolts. These disturbances are shown to be caused by any or all of the following: (1) insulating material in or near electron path; (2) irregularity of filament emission; (3) gas; (4) positive ions emitted by filament; (5) insulating or foreign deposits on grid wires. A tube has been developed in which the above effects are removed or reduced to a point where the disturbances are nearly that of the shot effect of the electrons, as limited by space charge. This allows the amplification of low-frequency voltages of less than 1 microvolt over the entire frequency band below 100 cycles.

INTRODUCTION

IT IS well known that, when vacuum tubes are used to amplify very small voltages at frequencies of less than 1000 cycles per second, great difficulties are encountered which are due to random disturbances occurring in the plate current of the first amplifying tube. The magnitude of these disturbances or noise varies from 10 to 1000 times that of the shot effect of the plate current of the first tube and is greatest at the lowest frequencies. This effect has been shown by J. B. Johnson[1] and was accounted for by him as a change in the activity of the electron emitting surface with time. The presence of space charge was shown to decrease greatly the noise produced in the plate circuit of a two element tube and to reduce the noise in a three element tube to a somewhat smaller extent. Johnson found no appreciable effect of gas pressure on noise in two element tubes. N. P. Case[2] has shown that, in a four element tube operated in the first stage of a standard radio receiver with an unmodulated carrier applied, the noise output in the last audiofrequency stage was considerably affected by the gas pressure of the tube under test at pressures greater than 10^{-4} mm of mercury; but at pressures below that, little effect was noticed. It should be noted that the noise measured by Case was the modulation impressed on the radiofrequency carrier in the first stage and did not include the low audiofrequencies below 60 cycles per second. Thatcher and Williams[3] have recently investigated the effect of space charge on noise in the radiofrequency range. With commercial tubes operated with space-charge limitation of plate current, the abnormal fluctuations in current were traced to the effect on the space charge of positive gas ions formed by collision between electrons and gas molecules and of positive metallic ions emitted by the

[1] J. B. Johnson, Phys. Rev. **26**, 71 (1925).
[2] N. P. Case, Proc. I.R.E. **19**, 963 (1931).
[3] E. W. Thatcher and N. H. Williams, Phys. Rev. **39**, 474 (1932).

filament. When these effects were eliminated by using specially built tubes having a high degree of vacuum, the noise output was reduced by the presence of space charge to an amount proportional to the ratio of the space current to the saturation current over a small range.

It was the purpose of this investigation to develop a commercial tube which could be used in the first stage of resistance coupled amplifiers which would have a very low ratio of noise output to amplification to allow the measurement of d-c. or low frequency a-c. voltages of a magnitude considerably smaller than previously possible.

Apparatus and Procedure

Two methods of indication of the noise voltage were used. The first was a three-stage resistance coupled amplifier terminating in a vibrating oscillograph element. The overall frequency characteristic, including the oscillo-

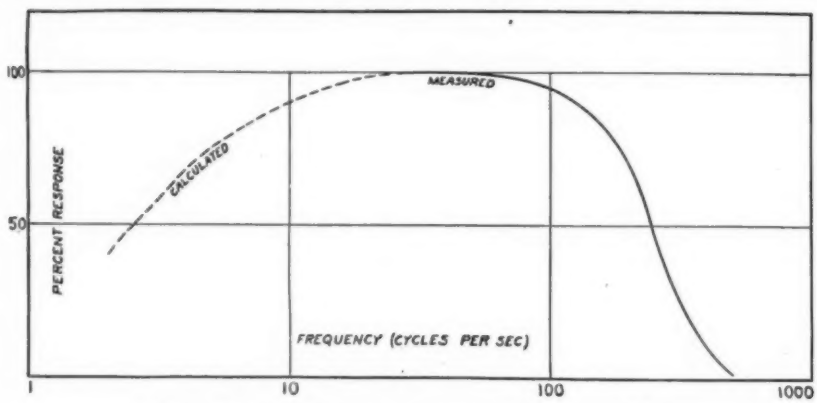

Fig. 1. Relative frequency response curve of amplifier.

graph element, was essentially flat from 1 to 500 cycles per second. Preliminary work with this equipment indicated that the frequencies of the major disturbances were below 200 cycles per second. A second amplifier was then constructed which allowed accurate measurement of the noise voltage over a narrower frequency band. This amplifier consisted of four stages of resistance coupled amplification employing screen-grid tubes and an output stage terminating in a thermocouple meter. The high-frequency response was cut off by use of shunt capacity after each stage. Fig. 1 shows the final overall frequency characteristic of this amplifier. It was desired to have as narrow a frequency band as possible to reduce the voltage due to thermal agitation and shot effects so that the random fluctuations would be the greatest percentage of the noise measured. The frequency band chosen accomplished this and yet included all of the major erratic disturbances present.

By removing the shunt capacity in the amplifier and decreasing the coupling capacity, the frequency band could be changed to cover a range of 300 to 100,000 cycles per second. Over this range all tubes gave fluctuation voltages which could be accounted for by space-charge limited shot effects and thermal agitation. As this result was well in accord with the observations on the os-

cillographic equipment and of previous investigations,[1] all further measurements were made using the frequency band shown in Fig. 1.

Because of the very high value of amplification necessary and the low-frequency range covered by the amplifier, external pick-up effects were serious. The methods used to eliminate microphonic disturbances from air or support vibrations are of little interest as the conventional lead-felt insulation and spring supports were sufficient. Effects of 60 cycle power lines were particularly strong. Means of eliminating them will be described in detail. Two effects were observed: first, a direct magnetic deflection of the electrons in the tube under test; and second, induced voltages in all the leads to this tube. The first effect, being quite small, was eliminated by the use of a magnetic shield consisting of three layers of 0.020″ transformer iron separated by layers of 0.020″ copper and, in addition, by the introduction in the grid circuit of a small voltage, derived from the interfering power line but 180 degrees out of phase with it. It is probable that in most localities the application of either of the above will be sufficient. The induced voltages in the leads were made

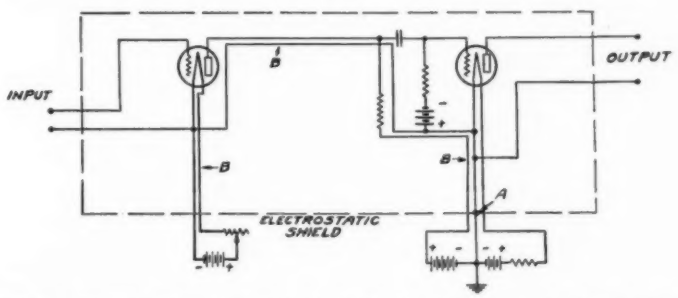

Fig. 2. Wiring diagram showing method of eliminating magnetic pick-up in first stage. *A*, electrostatic shield connected to amplifier at one point only. *B*, group all leads together. *C*, use no by pass condensers.

negligible by eliminating all possible linkages with disturbing magnetic flux. This was accomplished by wiring the amplifier as shown in Fig. 2. This method of connection is of utmost importance, as a loop 2 inches in diameter will link with enough flux to give a large deflection on the output meter.

Discussion

The observed disturbances, other than shot effect and thermal agitation, in amplifier tubes when the grid is operated with a negative bias could come from any of the following sources. Each of these was investigated in detail. (1) Charges collecting on the glass bulb and insulating materials in the tube; (2) insulating oxides on grid wires; (3) flicker effects in the filament emission; (4) gas present in the tube; (5) positive ion emission from the filament; (6) leakage over the base and stem.

Charges on the mica and lava insulating materials which would discharge at random were found to contribute a major portion of the disturbance in those tubes which showed the very largest fluctuations. Constructing the tubes so that electrons could not easily escape from the region within the

plate and charge up the bulb walls and insulation resulted in a material improvement.

The possibility of insulating oxides and dust particles on the grid wires charging and discharging and causing random noise was found to be of negligible importance, and then only when the parts were obviously contaminated.

Flicker effects in filament emission as described by J. B. Johnson[1] were very carefully investigated and at no time has any evidence been found that would indicate their having a measurable effect. This was shown particularly well when tubes were tested for shot and flicker effects by connecting grid and plate together and operating with an absence of space charge. In this case no correlation could be found between flicker effects and the disturbances observed with the same tubes operated as amplifiers. In most cases, even in the absence of space charge, the flicker effects were very small, being only a

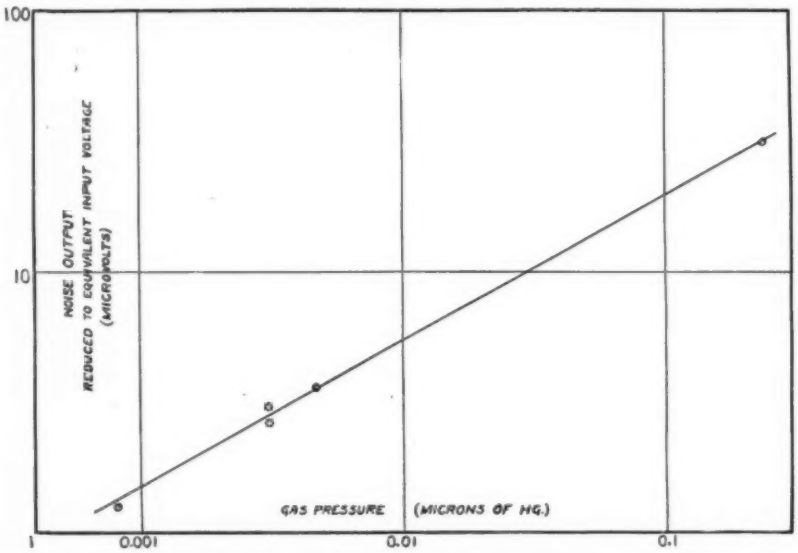

Fig. 3. Noise output vs. gas pressure.

few percent of the theoretical shot effect of the electrons unless high currents were used. This was found to be equally true of filaments of pure tungsten, thoriated tungsten, and oxide coated nickel. The absence of this effect in normal operation is also substantiated by the fact that, when certain other effects were removed, tubes were obtained which had a total noise voltage equal to that expected from the space-charge limited shot effect of the electrons.

Gas was found to be the one factor which always contributed large and definite amounts of disturbances. These disturbances were greatest at the lowest frequencies. The gas pressure in a tube was measured by connecting the tube as an ionization gauge as described by Dushman and Found.[4] Care was taken to prevent oscillation and to compensate for leakage currents. The curve shown in Fig. 3 is quite typical of a large number of tubes tested.

[4] S. Dushman and C. G. Found, Phys. Rev. **17**, 7 (1921); **23**, 734 (1924).

The slope varied somewhat between tubes and was possibly a function of the physical structure of the elements. The important point is that all tubes developed less noise with lowered gas pressure.

K. H. Kingdon[5] has shown how a slow moving positive ion may have a considerable effect on the space charge. One ion moving through the grid from the region of the plate to the filament may, because of its slow movement, neutralize as many as 600 electrons. An ion moving to the grid may oscillate around a grid wire as many as twenty-five times before finally striking it and hence will have its effectiveness increased many more times. This effect of positive ions on space charge can readily account for their effect on noise, even at very low pressures.

The high degree of vacuum necessary for a minimum amount of disturbance is obtained by very active getters and very careful exhaust. Positive ions emitted by the filament will, of course, produce the same effect as those liberated from gas molecules. Thus, they will contribute to the disturbances in the same manner. Quite a large number of tubes were tested for positive ion emission and noise without finding any correlation between the two. It is possible that their effect was so small that it was masked by the other disturbances present. This could be accounted for by the fact that, since the filaments were of thoriated tungsten, the operating temperature was low.

Excessive leakage currents over the base and stem were found to contribute a large amount of noise. A measurable amount of noise is obtained if this leakage resistance is less than 10^{10} ohms.

Results

Having found the factors causing noise in commercial tubes, it has been possible to develop a new tube in which all factors other than shot effect have been reduced to a negligible value and which operates with the space current reduced to a small value by the artificial space charge effect of the control grid, thereby reducing the shot effect to a small value, as shown by Thatcher and Williams.[3] Thus the noise developed in the tube is a function of the width of the frequency band and is independent of the frequency itself. This tube is designated commercially as the General Electric type PJ-11

Table I. *Comparison of noise output of various amplifying tubes*

Type	Noise output (microvolts)	Voltage amplification	Equivalent input voltage (microvolts)
PJ–11	5–10	15	0.3–0.7
–222	52	20	2.6
–240	65	16	4.1
–112A (oxide-coated filament)	85	7.3	11.6
–201 (single crystal tungsten filament)	75	6.7	11.2
–201 (pure tungsten filament)	100	6.7	14.9
–201 (thoriated tungsten filament)	110	6.7	16.4

[5] K. H. Kingdon, Phys. Rev. **21**, 408 (1923).

TABLE II. *PJ-11 Ratings and data*

Filament		*Conditions for resistance coupled amplification*	
Voltage	5 volts	Supply voltage (max.)	180 volts
Current	0.25	Grid bias	−1.5 volts
Type	Thoriated tungsten	Load resistance	100,000 ohms
		d-c plate current	0.45 m.a.
Average characteristic values at $Eb = 135$ v and $Ec = -1.5$ v		Voltage amplification	15
		RMS noise voltage (expressed as equivalent voltage applied to the grid and integrated over a 200 cycle frequency band)	0.5 microvolts
Plate current	0.45 m.a.		
Amplification factor	30		
Plate resistance	100,000 ohms		
Mutual conductance	0.3 m.a./volt		

Pliotron. Its ratings are shown in Table II and its characteristic curve in Fig. 4. A comparison of this tube with other commercial tubes is shown in Table I.

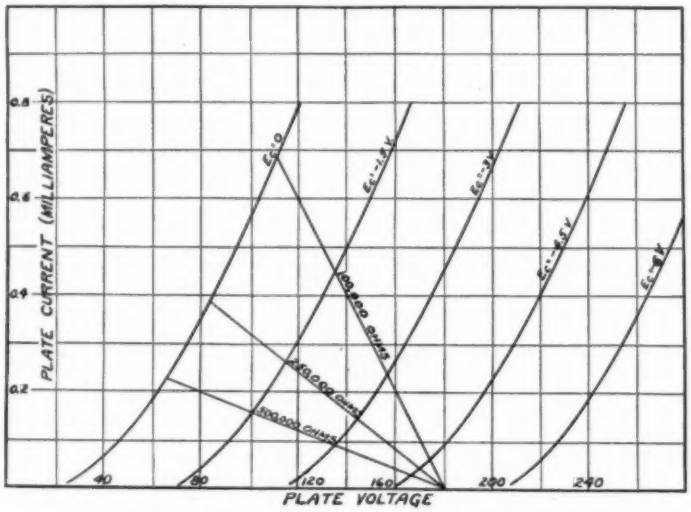

Fig. 4. PJ-11, average characteristic curves.

The two values of noise indicated for the PJ-11 represent the maximum and minimum noise that may be developed in this tube when operated at the normal conditions shown in Table II. The values given for the other tubes are merely representative of the magnitude of the noise produced by an average tube of each type. Values of noise have been measured on large numbers of these tubes and vary from tube to tube, from time to time, and from somewhat smaller to considerably greater values than the average.

The noises produced in the tube appear as noise voltages across the external resistance in the plate circuit. The noise voltage produced by the PJ-11 tube, being almost entirely space-charge limited shot effect and thermal agitation, can be expressed by the formula[6]

$$E_n = KR_p \qquad (1)$$

[6] Hull and Williams, Phys. Rev. **25**, 147 (1925).

where E_n is the RMS value of the total noise, K a constant depending on the space current and the area under the relative frequency response curve, and R_p is the external resistance in the plate circuit. Since the voltage amplification of the tube is given by the well-known formula

$$A_v = gm\left[r_p R_p/(r_p + R_p)\right] \tag{2}$$

where gm is the partial derivative of space current with respect to control grid voltage and r_p is the internal plate resistance of the tube, the ratio of noise voltage to amplification, referred to in Fig. 4 as equivalent input voltage, can be expressed by

$$\frac{E_n}{A_v} \frac{K}{gm}\left(1 + \frac{R_p}{r_p}\right). \tag{3}$$

This will be a minimum when the external plate circuit resistance, R_p, is reduced to zero. Thus by operating the tube with a small external resistance with consequently small gain, greater sensitivity is obtained. However, with the first tube having a small gain, the noise produced in the second tube becomes of importance. Either a second PJ-11 must be used in the second stage or a compromise made by operating with a higher gain and a decreased sensitivity. The conditions given in Table II represent the best operation using one PJ-11 coupled to a screen-grid amplifier using standard tubes. It may be necessary even under these conditions to select a quiet tube for the first tube after the PJ-11. With this arrangement of tubes and with the amplifier built as previously described, the residual noise in the amplifier will be only that due to space charge limited shot effect and thermal agitation voltages. A frequency band of 200 cycles width, even at the lowest frequencies, may be covered with a noise voltage equivalent to only a few tenths of a microvolt applied to the input. This noise voltage will be steady enough in value so that the output indicating device can be balanced to zero and voltages may be measured accurately as low as 0.1 microvolt. If the frequency band is narrowed, as could be done for measuring a single frequency, the minimum measurable voltage is decreased proportionally as the square root of the area under the relative frequency response curve. Thus a tenfold reduction may easily be obtained.

In conclusion, we wish to express our indebtedness to Mr. B. J. Thompson who contributed much to the early work herein described.

Preliminary Note on a New Magnetometer*

By C. A. HEILAND[1]
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(Received May 11, 1932)

A vertical magnetometer is described which is believed to fill the need for an intermediate type between the dip needle and the Schmidt balance. It does not require a tripod and levels itself. The compass for orienting remains attached to the instrument; it may also readily be compensated for temperature. It utilizes a magnetic system suspended in jewels in or near its center of gravity; the magnetic vertical intensity is balanced by the torsion of a helical spring. The magnetic system is adjusted to the normal vertical intensity in the area under survey by a suitable setting of the spring and the anomaly is roughly proportional to the angle of deflection from the horizontal.

THERE exists a tremendous variety of all kinds of magnetic variometers. The great number of magnetic instrument types is due chiefly to two reasons: First, the Earth's magnetic field may be resolved into quite a few intensity and angular components, each of which may be measured by suitable apparatus. Secondly, the number of forces which may be utilized in intensity measurements for comparison with a magnetic force is equally great; they may be magnetic, electromagnetic, gravitational or elastic in nature.

It requires an explanation, then, why there would be an advantage in adding another magnetometer to the long list of magnetic instruments. The purpose of the following is to show that there is actually a need for a field magnetometer which represents an intermediate between the well-known dip needle and the magnetometers which have been developed lately, such as the Schmidt field balance and the Hotchkiss Superdip.

The field procedure used in magnetic prospecting is to measure the anomalies of the Earth's magnetic field at a number of suitably arranged field stations. A certain time is required to occupy each station and make the necessary observations. Although the magnetic method is probably the most rapid of all geophysical methods, there is still a possibility to reduce the time required for each set-up by so constructing a magnetometer that a number of operations may be left out, and still obtain an accuracy which is consistent with the purpose at hand.

During the time in which geophysical methods have been applied in this country, their range of application has become fairly well known. Experience has shown that the magnetic method is chiefly useful as a preliminary one, which should be followed up by other geophysical measurements which offer a better opportunity for a quantitative interpretation. This holds primarily for the application of the magnetic method in oil prospecting, and disregard for this fact has at times given rise to adverse criticism of the method. On the other hand, the petroleum geologist who may be inclined to view the pos-

* Read before the American Association of Petroleum Geologists at the Oklahoma City meeting, March 25, 1932, and printed in *Physics* by permission of the A.A.P.G.

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sibilities of the magnetometer too critically should be reminded of the fact that excellent successes have been obtained with quantitative magnetometer interpretation in prospecting for orebodies. Many failures of the magnetic method have resulted from the fact that observers were not well enough acquainted with the geologic variables which enter into the magnetic results, and were inclined to see things in a magnetic map which did not exist.

If it is true, then, that according to experience, the principal function of the magnetic method in oil work is "to pick up anomalies," it follows that such reconnaissance work should concentrate upon finding such geologic conditions which can readily be located with the magnetometer, and are, therefore, of such magnitude to warrant further geophysical and geological exploration.

To express this quantitatively, experience with magnetic prospecting in the majority of areas on this continent shows that not much significance can be attached to a magnetic anomaly unless a number of closed contours can be drawn at an interval of 50 gammas.

For such type of anomalies, the Schmidt vertical balance is almost too sensitive. Stating this in a different manner, the time required to set up a tripod, level it, orient its top by means of a compass, remove the compass, set up the instrument, relevel it, read the scale in two azimuths three times and to read the temperature and possibly the time, seems somewhat out of proportion when the required accuracy is not greater than ± 25 gammas. On the other hand, a dip needle, in the operation of which most of the steps enumerated above are not required, will not give this accuracy.

It appears, therefore, that an advantage may be gained if there were an instrument available which could be operated like a dip needle and would still give the accuracy required for the purpose outlined above. It is believed that the magnetometer described below will fulfill such requirements.

The principal feature of the new magnetometer is that the use of a tripod, and the necessity of levelling, of removing the compass and of making temperature corrections is eliminated.

Principle of the Instrument

The instrument is a vertical intensity magnetometer. The comparison force which balances the magnetic vertical intensity is furnished by the torsion of a helical spring. The magnetic system is so suspended that the axis of revolution coincides as nearly as possible with its center of gravity, although no particular disadvantage would arise from having both elastic and gravity forces acting on the system. If a magnetic system is suspended in its center of gravity, with its plane of oscillation at right angles to the magnetic meridian, then its longitudinal axis would adjust itself into a vertical position; i.e., into the direction of the vertical intensity.

The helical spring is mounted, with its plane vertical, next to the magnetic system. One end of it is attached to the magnetic system, and the other end is fastened to a movable arm which may be revolved about a horizontal axis by turning a pointer on a graduated scale on the back of the case.

The working principle of the apparatus is adapted from a type of horizontal magnetometer which is frequently used in magnetic observatories. A magnet is suspended from a torsion wire so that it is free to oscillate in a horizontal plane. If the torsion of the wire is small as compared with the magnetic couple, the magnet will adjust itself into the direction of the magnetic meridian. Or else, the magnet may be so fastened to the magnet and the adjustment of the torsion head may be so made that the wire is without torsion when the needle points in the direction of magnetic North. In order to measure the horizontal intensity with this magnetometer, the torsion head is now turned until the magnetic system is at right angles to the magnetic meridian. Then the horizontal intensity is balanced by the torsion of the suspension wire.

In the vertical magnetometer herein described, the helical spring is so attached to the magnetic system and the pointer on the back of the case is so adjusted that the spring is practically without torsion when the magnetic system stands vertical. Then the pointer is moved and the spring is twisted until the magnetic system is in a horizontal position. If τ is the torsional coefficient of the spring, and ψ is the angle through which the pointer was turned to bring the magnetic system into the horizontal position, the equilibrium of the forces acting on the magnetic system leads to the equation

$$MZ_0 = \tau\psi$$

where M is the magnetic moment of the needle and Z_0 is the (normal) magnetic vertical intensity for which the instrument has been adjusted. At any other station where the anomaly in the vertical intensity is ΔZ, a deflection equal to the angle ϕ is obtained, so that

$$M\Delta Z \cos\phi = \tau\phi$$

or, with sufficient approximation for small angles, $\Delta Z = \phi \cdot \tau / M$, where τ/M is the scale value of the instrument. It is readily seen that the sensitivity of the instrument increases with the strength of the magnetic needle, and with the ease with which the spring can be twisted.

For larger deflections, the difference of $\cos\phi$ from 1 can not be neglected. The most practical way to take this into account is to consider a variation of scale value with deflection; that is to say, a standardization chart may be used showing the vertical intensity anomaly as a function of angular deflection. Such a standardization curve may be readily prepared by placing the magnetometer in a Helmholtz coil, and by varying the field.

The described instrument has a number of features in common with the Dahlblom pocket magnetometer for the horizontal and vertical intensity.[2]

In Dahlblom's instrument, also a helical spring is used to balance either horizontal or vertical intensity. The difference is, however, that in Dahlblom's instrument the pointer on the back of the case has to be adjusted at every station to bring the magnetic system into the horizontal position, the pointer

[2] E. Haanel, On the location and examination of magnetic ore deposits by magnetic measurements, Ottawa, 1904, p. 99–105.

reading thus being a measure for the observed intensity; in addition, the Dahlblom instrument does not have the self-levelling and orienting feature, and does not furnish the accuracy of the described instrument.

Self-Levelling Feature

As shown in the figure, a fairly long bar is attached to the magnetometer case, which ends in a gimbal suspension on the top. The observer holds the instrument by means of two handles, and the magnetometer adjusts itself into a vertical position. Therefore, the axis of rotation of the magnetic system will always be horizontal, and a line passing through the two zeros of the

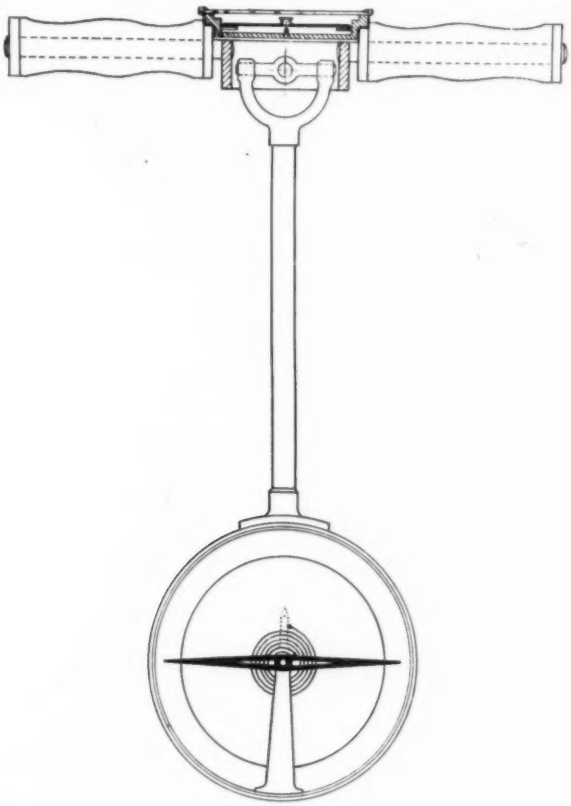

Fig. 1.

graduation will also be always horizontal. In manufacturing the instrument, attention is given to the fact that the bearings are level when the case is vertical.

Therefore, there is no need to observe in two azimuths of the instrument, the principal purpose of which (in the Schmidt magnetometer) is to eliminate errors due to a deviation of the axis of revolution of the magnetic system from the horizontal and to improper levelling (besides eliminating errors due to misorientation).

Orientation

The compass used for orientation of the case into a direction at right angles to the magnetic meridian is permanently attached to the instrument and is mounted on the upper ring of the Cardan suspension, between the two handles (see Fig. 1). It is released by pressing a button mounted on the one handle within the reach of the thumb of the observer's hand gripping the handle. The fact that the compass is permanently attached to the instrument does not impair the accuracy of the readings in any way for a number of obvious reasons. First, the compass magnet is removed from the magnetometer magnet and its field is small; secondly, this field is constant because of the constant distance of magnetometer and compass magnet; third, if it was not constant, the field of the compass magnet would still be at right angles to the magnetometer magnet and, therefore, be without effect.

Reading the Instrument

When a station is occupied, the observer holds the instrument in front of him, releases the compass and turns until the end of the compass needle coincides with the index on the circle. To take the reading of the magnetometer, he keeps looking in the same (vertical) direction and reads the position of one end of the magnetometer needle on the graduated scale, the image of which is projected upward by a mirror attachment (not shown in the figure). The magnetic system is suspended in jewelled bearings; during transportation, one end of the needle is held in a clamp so that it can not swing with great amplitudes and damage the spring. When the instrument is taken out of the case to make the measurement, this clamp is released.

Temperature Compensation

The construction of the magnetometer makes it possible to compensate it against temperature, as the helical spring may be so attached to the magnetic system that its expansion offsets the upward movement of the North pole of the magnetometer magnet. The compensation is consistent with the accuracy required of the instrument, so that an installation of a thermometer, and temperature readings become unnecessary.

Performance of the Instrument

The instrument should have its principal application in rapid reconnaissance surveys where the accuracy furnished by a Schmidt balance is not required. In particular, it should prove useful under difficult terrane conditions, and where a steady support for a magnetometer is lacking; it may be operated on a canoe, or on horse- or mule-back, provided that parts made of iron or steel about the means of transportation are sufficiently removed.

The above represents a preliminary account of the instrument which has been built by Mr. Charles H. Hull in the precision shop of the Colorado School of Mines. Tests are being made to determine its sensitivity for different spring materials, its reaction to temperature changes, its mean error when reoccupying a station, and to determine its performance and field worthiness under varying conditions. These data will be published in a subsequent paper.

On the Rôle of the Electric Wind in Electrical Precipitation in Gases

By EVALD ANDERSON
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(Received April 25, 1932)

1

THERE has been considerable discussion, in the past year, chiefly between German physicists and engineers,[1,2] on the role played by the electric wind in the electrical precipitation process.

On the one side it is held that the electric wind, through its effect on the motion of the particles towards the collecting electrode is the determining factor in the process, while on the other side it is argued that the net action of the wind is nondirectional and that its chief rôle is to promote uniform distribution of the particles in the gas.

Electric wind is the name given to the motion of neutral gas molecules, or to neutral gas molecules and gas ions caused by the motion of the latter in an electric field. It is obvious, therefore, that it is associated with all electrical conduction through gases. It becomes particularly noticeable, however, in gases at ordinary pressure when the ion flow is unidirectional and the current fairly large, as for example, where the electrode arrangement is unsymmetrical as in the point-to-plate type, ordinarily used in the electrical precipitation process.

In such point-to-plate electrode arrangement the ions are generated through ionization by collision in the strong electric field near the electrode with the smallest radius of curvature. The ions of opposite sign to this electrode are then attracted to its surface and neutralized, while those of the same sign move through the gas towards the opposing electrode. There is thus set up a motion of the gas from the ionizing or discharge electrode, to the opposing, or collecting electrode, and this motion is ordinarily of sufficient magnitude to be easily detected, although its exact measurement is difficult. The motion of gases in any closed system must obviously be continuous and the electrode arrangement is ordinarily such as to necessitate a return motion of the gas back to the discharge electrode. However, the movement in the one direction is ordinarily concentrated in a small region with a high gas velocity, while the return movement is diffuse, with a very low gas velocity, and this latter is, therefore, not so readily detected.

The initial ions in gaseous electrical conduction are either charged atoms and molecules, or electrons. At ordinary pressures, the electrons probably soon attach themselves to neutral molecules, to form negative gas ions, and

[1] R. Ladenburg, U. W. Tietze, Ann. d. Physik [5], **6**, 581 (1930).
[2] Walther Deutsch, Ann. d. Physik **9**, 249 (1931).

these often become attached to neutral molecules to form so-called cluster ions.

The electrical precipitation process consists in the "ionization" of suspended material particles through adhering gas ions, and the consequent motion of these "ionized" particles to the collecting electrode under the action of the electric field.[3] The rate of motion of both particles and gas ions is obviously of great interest. The rate of motion of gas ions in a given electric field, or their mobility, has been investigated from the very beginning of the study of electrical conduction through gases. In most investigations the ions are formed through some outside agency, and at a relatively slow rate so that the number of ions involved is relatively small; and the fundamental assumption has always been made that the rate of motion is proportional to the strength of the electric field. This assumption presupposes that the ions, accelerated by the electric field between collisions with neutral molecules, are brought to rest at the end of their free paths, and that on the average the neutral molecules are not moving in the direction of the field.

Where the currents and ion concentrations are very small such conditions undoubtedly prevail so that the ion mobilities calculated correspond closely with actual values. However, these ion mobilities obviously refer to still gas and, therefore, represent relative velocities with respect to the surrounding gas-molecules.

In point-to-plate fields conditions are very different, since here the ion concentration is ordinarily high enough to cause an appreciable motion of the neutral gas molecules. If the mobility be assumed the same as ordinarily determined, this would merely be the mobility with respect to the gas. To find the actual velocity, with respect to the electrodes, it is obviously necessary also to know the velocity of the neutral gas molecules in the direction of the field, which, incidentally, has never been satisfactorily determined. In one of the first attempts to measure the ion mobility in this type of field[4] the quantity measured was the velocity pressure of the neutral gas molecules. The actual velocity of these molecules was not considered, and it is doubtful if either the experimental arrangement or the theoretical basis for the calculation, justify the faith since then placed in the results obtained.

The magnitudes of the current and ion concentration are ordinarily of an entirely different order in point-to-plate discharges from their values in the ordinary gaseous conduction with outside ionizing agents. The current-voltage characteristic for these discharges is usually given as:

$$I = AV(V - V_0)$$

where I is the current, V the voltage, V_0 the ionization or starting voltage, and A is a constant. The current thus increases very rapidly with the voltage above V_0. This relation, however, only holds at voltages not too far removed from this starting voltage. For higher voltages the current increases still more

[3] One of the writers already quoted has, however, suggested that the moving neutral gas molecules may carry a major portion of the particles.

[4] Chattock, Phil. Mag. **48**, 401 (1899).

rapidly until when the critical voltage, V_m, is reached, a complete breakdown occurs and the magnitude of the current is only limited by the resistance of the rest of the circuit.

The voltage region of the electrical precipitation process is always very near this breakdown voltage, so that the ion concentrations are very high. The discharge, or ionization electrodes used in this process are usually small cylinders or wires, and not points, but the discharge nevertheless takes place from points at the surface of the electrode, particularly when its polarity is negative. As the critical voltage is approached visible streamers tend to form from the discharge electrodes and extend through the gas nearly to the opposing electrode and it is likely that in this case the greater part of the current is not only initiated at points, but is carried through the gas in pencils of comparatively small cross section.

Such a condition should naturally be impossible with ions of only one sign, since these would repel each other and tend to become uniformly distributed in the field. It has been suggested, however, that in these streamers, ionization takes place at lower voltages, as a result either of step ionization or of radiation from the rapid recombination of the ions so that in these regions there may, therefore, be not only ions, ion clusters and mechanically transported neutral gas molecules, but also electrons. It can, therefore, undoubtedly be taken for granted that here the velocity of the ions is not proportional to the electrical field.

It is obvious that ordinary methods for the determination of ion mobilities are entirely inapplicable to this problem and no satisfactory special methods have apparently yet been devised, either for measuring the mobilities relative to the gas or the velocities of the gas streams relative to the electrodes.

The mobility of singly charged gas ions in still gas at atmospheric pressures and in nonionizing fields is between one and two centimeters per second in a volt per centimeter field, so that in an ordinary precipitation field of about 50,000 volts for an electrode spacing of 10 centimeters, the velocity of such ions may be about 50 meters per second. This must undoubtedly be considered as the minimum velocity of the ions in the less active regions of such strong point-to-plate fields. Near the center of the streamers where a preponderance of the molecules may be ionized and where electrons might carry an appreciable part of the current, the velocities are undoubtedly nonuniform and of an entirely different order of magnitude.

One might, therefore, visualize such ion streams as a core of very speedy ions in the center (with the discharge electrode negative there are probably also electrons) moving with a very high nonuniform velocity. Surrounding this core would be a region of ions, moving through and with a stream of neutral gas molecules (which latter have acquired energy and velocity from the moving ions), with velocities, relative to the moving neutral molecules, of the order usually ascribed to gas ions, but whose actual velocities relative to the electrode may be considerably larger. Finally on the outer edge of this region there may be ions moving through relatively quiescent gas, whose actual velocities are those to be expected from the mobilities of small ions in nonionizing fields.

To attempt to deduce actual ion-mobilities from the average velocity pressure of such electric wind or streams of ions and molecules, or to assume that the velocities of these ions, relative to the electrodes, can be deduced from the measured mobilities of ions in nonionizing fields, seems wholly unjustifiable. All that one is justified in stating is that the ion mobility relative to the gas probably varies from about one centimeter per second (for simple ions) to a much higher nonuniform mobility, while the mobility relative to the electrodes is this relative mobility plus the velocity of the immediately surrounding gas-streams. For simple gas-ions, (i.e., with a single charge per gas molecule) the figure given for electrical precipitation fields of 50 meters per second can, therefore, be assumed as the velocity of the slowest ions.

2

This complex stream of moving ions and gas molecules is the setting and the means for the electrical precipitation of suspended particles from gases. Most writers on the theory of the process have assumed that it consists merely in the transportation of charged particles through the gas to the collecting electrode and that the rate of precipitation is determined by the rate of motion of such charged particles in the corresponding electrical field. But it is obvious that the process is made up of three parts; i.e., (1) "ionization" or charging of the particles, presumably by the attachment of one or more gas ions; (2) transportation of the charged particles to the electrodes; and (3) deionization of the particles at the electrodes. Any satisfactory theory must necessarily take account of all three parts.

Elaborate experiments made by electrical precipitation engineers in California in 1919 demonstrated that with suspended particles that do not tend to hold their charge, the net precipitation rate for a given electric field could be accurately represented by the relation:

$$1 - E = K^t.$$

Where E is the fractional part of the particles precipitated in the time t and K the so-called precipitation constant,[5] and it was shown that this equation follows directly from the assumption that the precipitation rate $-dc/dt$ is proportional to the fume concentration c in the gas.

Before this it had been recognized that the rate of precipitation was independent of the concentration of the particles and the above equation obviously can also be deduced from that relation.

We can measure accurately the total or net rate of precipitation, but the attempts which have been made to measure either the rate of ionization or the rate of transportation, have given very doubtful results. Except for a few attempts to directly measure the velocities of the particles, the almost universal method has been to either measure or deduce the relation between the size and charge of the particles and then to calculate their velocity in the electric field by the use of Stokes law. Even if this law did apply to the relative motion of particles in a moving gas, which is doubtful, it is obvious that

[5] Chem. and Met. Eng. **26,** 151 (1922); Ind. and Eng. Chem. **16,** 1028 (1924).

in order to calculate the actual velocity it would be necessary to know both the velocity of the charged particles with respect to the gas, and the velocity of the latter with respect to the electrodes.

The chief arguments advanced in favor of the direct influence of the electric wind on the precipitation rate has been that this rate is far greater than should follow from the transportation velocities calculated; but it is obvious from what has been said that not even approximately accurate estimates can yet be made as to the actual velocities of such charged particles, and that the precipitation rate may not be determined by the transportation velocity.

Visual observation of the precipitation action leads to the conclusion that the transportation is extremely rapid, while the time required to precipitate even 90 percent of the particles may be several seconds. Furthermore, accurate experiments have shown that the rate of precipitation does not vary inversely as the precipitation distance (i.e., radius of the cylinder in cylindrical electrodes) as it should do if the transporation rate, or velocity of the particles in the direction of the field, were a determining factor. Rather it tends to vary approximately as the square of the distance. For example, if the time required to precipitate one-half of the weight of the suspended matter in a given volume of gas be taken as a basis of comparison, then for a certain easily precipitable mist this time $t_{\frac{1}{2}}$ is about 0.07 seconds, where the electrode distance is 7.5 centimeters, and 0.25 seconds, when this distance is 15 centimeters.

Neither is this time affected by the size of the particles as has been deduced from the calculated mobilities of such particles, although here so many divergent results have been obtained by the different investigators that it is difficult to make comparisons with data from actual practice.

All of these observations of actual electrical precipitation phenomena lead to the conclusion that with conducting particles the total rate of precipitation may be determined as much by the rate of ionization as by the rate of transportation, while with relatively nonconducting particles that tend to hold their charges the rate of deionization is always the determining factor. In other words, the time required to ionize a given proportion of the particles in a gas may be longer than that required to transport them to the collecting electrode and to deionize them, when the particles are relatively conducting and do not tend to hold their charges; while, with the relatively nonconducting particles, the time required for deionization is always longer than that required both for ionization and transportation.

The electric wind may here play a twofold role. It may tend to agitate the gas, thus promoting uniform distribution of the particles and facilitate their ionization. It may also directly affect the transportation rate of the particles, through the superposing of an additional velocity on the relative velocity of the ionized particles and also perhaps through the mechanical transportation towards the collecting electrode of unionized particles by unionized gas molecules, since the speedy motion of the gas towards the collecting electrode must have much more effect on the suspended particles than the comparatively slow and "diffuse" return of the gas towards the discharge elec-

trode. The net result is that through this action of the electric wind more energy and velocity can be imparted by the electric field to the particles than would occur merely through the probable charge on the particle. In so far as the electric wind thus affects the ionization or transportation rates, where these are the determining factors of the total precipitation rate, one might say that the electric wind affects this total rate.

It is, however, not necessary to postulate any major effect of the electric wind on either the ionization or transportation rate in order to explain the observed precipitation rates; nor is it likely that our present knowledge of these processes would permit us to evaluate such an effect if it exists. Moreover, in that large proportion of practical applications where the rate of deionization is the determining factor, the electric wind can have no direct effect on the precipitation rate.

Eötvös Torsion Balance

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The presence of an extra-heavy (or light) body in the sub-surface warps the level surfaces up (down) over the body and the lines of the vertical toward or into (away from) itself. The Eötvös torsion balance consists of a calibrated platinum-iridium torsion wire which supports a beam of negligible weight; a weight is attached to one end of the beam and a second weight is suspended from the other end. Curvature of the level surfaces and curvature of the vertical each produce at the two weights horizontal components of gravity which are respectively equal and opposite in actual but the same in rotational direction. The torque produced by the curvature of the vertical is a function of the difference of the radii of curvature of the level surface in the directions of major and minor curvature. There has been only one slight important improvement of the torsion balance in the past twenty-five years. There is room for improvement in the avoidance of temperature effects and in speeding up in the time necessary for observation. The mathematics of the torsion balance and of the gravitational effects of simple geometrical bodies is simple and developed. The main field of research with the torsion balance lies mainly in the geological-geophysical field of interpretation, although there are still unsolved problems in the mathematics of interpretation.

THE Eötvös torsion balance measures two gravitational quantities which reflect variation of density in the earth's crust.

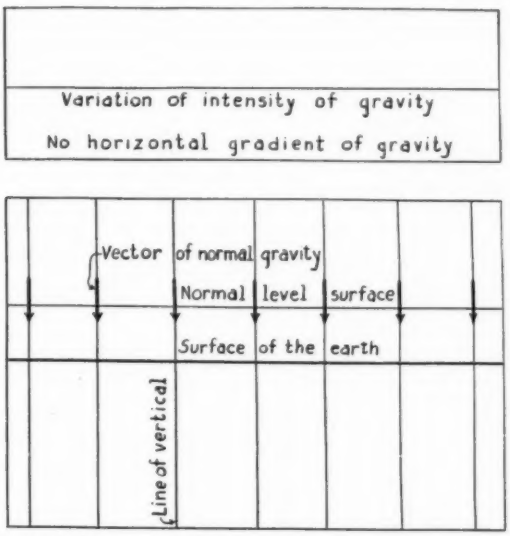

Fig. 1. Gravitational field in an area where the earth's crust is homogeneous and level.

If in a small area (Fig. 1) the earth's crust is homogeneous and level, then the lines of the vertical (lines of force of gravity) are straight lines perpendicular to the earth's surface, the level surfaces (equipotential surfaces) are parallel

to the earth's surface, there is no horizontal variation of gravity, and no horizontal gradient of gravity, and gravity may be represented by vector arrows which will be perpendicular to the earth's surface and whose length will be constant at any elevation but will decrease slightly with increasing elevation (0.308 millidynes per gram per meter).

If an extra heavy-mass is introduced into the earth's crust, the extra-heavy mass will exert a gravitational attraction which can be represented by vector arrows which will fly radially toward the extra-heavy mass and whose length decreases rapidly with increasing distance according to the Newtonian law:

$$k\delta \int_{d,e,f}^{a,b,c} \left[\frac{1}{(x^2 + y^2 + z^2)} dx\,dy\,dz \right].$$

The magnitude and direction of gravity at any point will be represented by the resultant of the two vector arrows. From Fig. 2, it can be seen that the lines of the vertical will be drawn in toward the center of the extra-heavy mass

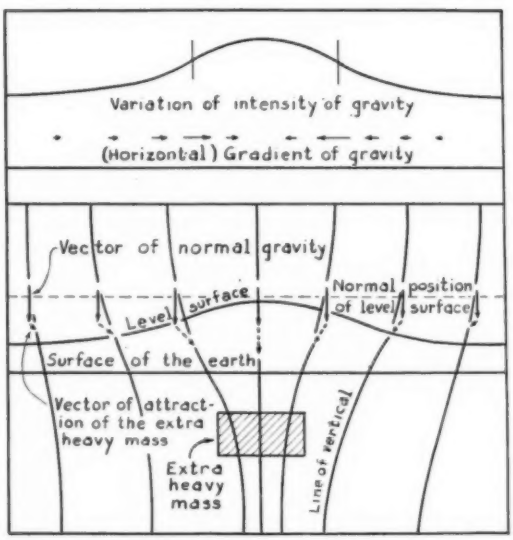
Variation of intensity of gravity
(Horizontal) Gradient of gravity
Vector of normal gravity
Level surface
Normal position of level surface
Surface of the earth
Vector of attraction of the extra heavy mass
Extra heavy mass
Line of vertical

Fig. 2. Gravitational field in the same area, if an extra-heavy mass is present in the sub-surface.

and that the level surfaces will be arched up over it. Gravity will be at a maximum above the center of the heavy mass and decrease in each direction to normal gravity as an asymptote. From each side, there will, therefore, be a gradient in toward the position of the center of the extra-heavy mass (see Fig. 3).

The Eötvös torsion balance consists essentially of a thin, carefully calibrated platinum-iridium (or tungsten) torsion wire, from which is suspended an aluminum bar of essentially no weight. A gold or platinum weight is fastened to one end of the bar and a similar weight is suspended by a fine wire from the other end. A mirror is carried on the axial stem of the bar. By

use of a telescope with vertical cross hair and of a scale reflected in the mirror, it is possible to measure the horizontal rotation of the bar and by use of the instrumental constants, the torsion constant of the torsion wire, and the angle of deflection of the bar, it is possible to calculate the force which caused the deflection of the bar.

The small section of space around a torsion balance in Fig: 2 is represented in magnified form in Fig. 3. The curvature of the level surfaces can be seen to produce at the two weights, horizontal components of gravity which will be equal and which will be opposite in actual but the same in rotational direction. This couple in general will have a component perpendicular to the bar and will rotate it until the resistance of the torsion wire equals the moment of rotation. The curvature of the lines of the vertical through the space of the torsion balance can be seen also to produce at the two weights, horizontal

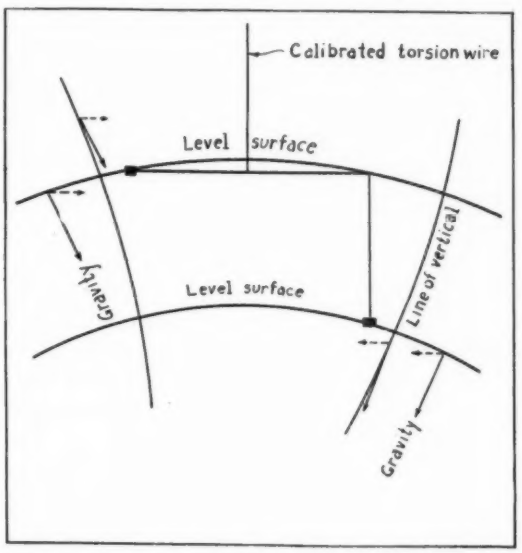

Fig. 3. Gravitational field as it affects the torsion balance in Fig. 2.

components of gravity which will be equal and which will be opposite in actual but the same in rotational direction and which will also rotate the bar.

The horizontal components which are caused by the curvature of the level surfaces can be proved to be proportional to gravity times the difference between the reciprocals of the major and minor radii of curvature of the level surfaces. The quantity is called the differential curvature of the Eötvös curvature value.

The gradient and differential curvature are measured in Eötvös units (E), which are units of 1×10^{-9} dynes per gram per horizontal centimeter, or cm per sec. per sec., per horizontal centimeter. The observed values of the gradient and differential curvature most commonly range from 0 to 30E but values as large as 150E are observed occasionally.

The total force acting on the bar at any place is a function of the two couples, the one proportional to the differential curvature and the other to

the gradient. It is given by the following equation: $N_1 - N_0 = \frac{1}{2} K U_\Delta \sin 2\alpha + K Uxy \cos 2\alpha - M Uxz \sin\alpha + M Uyz \cos\alpha$, where N_1 = the scale reading, N_0 = the zero point of the instrument, M and K = instrumental constants, α = the azimuth of the balance, $U_\Delta = (\partial^2 U/\partial y^2 - \partial^2 U/\partial x^2)$ and $Uxy = \partial^2 U/\partial x \partial y$ the components of the differential curvature, Uxz = the $N-S$ component of the gradient $\partial^2 U/\partial x \partial z$ and Uyz = the $E-W$ component $= \partial^2 U/\partial y \partial z$, and U = the Newtonian gravitational potential function.

The modern instruments ordinarily are observed in azimuths of 0°, 120°, 240°, 0°, 120° · · · . Each instrument consists really of two independent instruments oriented 180° apart. Each reading of the instrument, therefore, gives two values for the equation. The equation contains six unknowns, U_Δ, Uxy, Uxz, Uyz, and the N_0's of the two instruments. Three readings mathematically are sufficient to calculate all the unknowns. The fourth, fifth, and successive readings are made to check, and correct for, the rather common shift of the zero point.

The observed values of the gradient and differential curvature reflect all the appreciable differences of density around the torsion balance and are the resultant of the effects of: (a) topographic irregularities, (b) the planetary variation of the gravitational field from the equator to the poles, (c) small, relatively shallow geologic features, (d) boulders and other variations of density in the sub-soil close under the instrument, (e) medium-sized structures, (f) very large, in many places very deep geologic structures.

Corrections are applied for the topographic and planetary effects. The sub-soil effects are averaged out by taking sufficient stations sufficiently scattered. The residual anomalies then reflect major differences of density in the sub-surface, which in general are to some degree associated with sub-surface structure.

Different classes of geometric form of the extra-heavy or extra-light bodies in the sub-surface produce different classes of gradient and differential curvature anomalies at the surface. Each type of anomaly goes through certain variations of form and amplitude as the depth of the anomalous body varies. From the observed gradient and differential curvature anomalies at the surface, it may be possible to tell something about the form, general depth, and the relative density of the mass in the sub-surface, which is producing the anomalies. In a few situations, it is possible to make predictions with a fair quantitative accuracy but in general the predictions are only shrewd qualitative guesses.

Having made his interpretation of the probable distribution of density in the sub-surface which corresponds to the gradient and differential curvature anomaly, the geological-geophysicist attempts to interpret that distribution of density in terms of some geological structure which is probable or possible in the area. Definite and positive interpretation can be made in some places. In interpretation of surveys in the Gulf Coast, a certain type of anomaly could be said definitely to reflect a shallow salt dome; and another type could be said definitely to reflect a very deep dome (salt not rising within 7000 feet of the surface). But in other places with other types of anomalies, it may be

possible only to make a wild guess in regard to the geologic significance of the anomaly.

The success of the torsion balance in the Gulf Coast has been brilliant. Previously to 1924, forty-two salt domes had been discovered by geology and accident. The first torsion balance salt dome, Nash, was discovered in 1924, and now the torsion balance has to its credit the following salt domes: Sugarland (first class oil field), Nash (third class oil field), Long Point (commercial sulphur deposit), Clemens, Allen, Rabbs Ridge (good oil field), Manvel (fair oil field), Mykawa, (dubious oil field), Esperson (fair oil field), Hankamer (fair oil field): O'Conner Ranch (looks like good oil field), and has had some part in the discovery of the Cameron Meadows salt dome and oil field.

The field for research in connection with the torsion balance is much smaller than with the seismic and electric methods. The instrument itself is open to improvement in connection with shortening of the time of observation, with minimization or elimination of the shift of the zero point of the torsion wire under changes of temperature, and with decreasing the size and weight of the instruments. As it is, there has been no important change in the standard types of the Eötvös torsion balance for twenty-five years. The fundamental mathematical theory of the torsion balance and of the gravitational theory of the interpretation of torsion balance surveys is well known. The advanced mathematics of the interpretation of torsion balance results offers some room for research, but in large part is impracticably difficult. Field observations of the gradient commonly may have an error of 1, 2, or 3E; and, of the differential curvature a much larger error. It is seldom possible to obtain a complete picture of an anomaly; the outer ends of the anomaly beyond the points of one-third maximum commonly are obscured by extraneous anomalies. The density relations commonly are not known. There is, therefore, an interesting but small problem of research in connection with the families of simple geometric bodies which might produce a given observed gradient or differential curvature profile with a probable error of ± 0.5E to ± 1E. Most areas and geologic structures present such complicated arrangements of density differences that it would be impossible to handle analysis of them analytically, even if the distribution of density were known, and in most places, the density relations will be known only qualitatively. The distribution of density in many places may be simplified sufficiently for approximate analysis by graphical methods. Research on the advanced mathematics of interpretation of torsion balance results seems to offer a rather sterile field.

A broad and fertile field for research, however, lies in the geological-geophysical phase of interpretation; i.e., in the study of the types of anomalies which are produced by different geologic structures and situations, in the study of the density of formations (not of hand specimens), in the interpretation of areal gravity surveys, and of the normal variation of gravity in specific areas, and in the accumulation of general experience in the application of the torsion balance method of the working of geologic structure.

Examples of actual torsion balance surveys of known geologic structures are shown by Figs. 4–8. The Nash salt dome was discovered on the basis of

the gradient arrows of the survey, which is shown in Fig. 4. The heavy dashed lines represent the 1000 foot and 4000–5000 foot structure contours which were predicted by the writer in advance of drilling and which were based wholly on those gradient arrows. The dotted lines are structure contours which were based on subsequent drilling and show the degree of verification of the predictions. Nash was the first dome discovered in the Gulf coast by means of geophysics. The cross section of the Nash dome is much the same as that of the South Liberty-Dayton salt dome at the left in Fig. 6. Esperson is a deep salt dome which was discovered on the basis of the geophysical survey which is shown in Fig. 5. The salt is known only from the geophysical

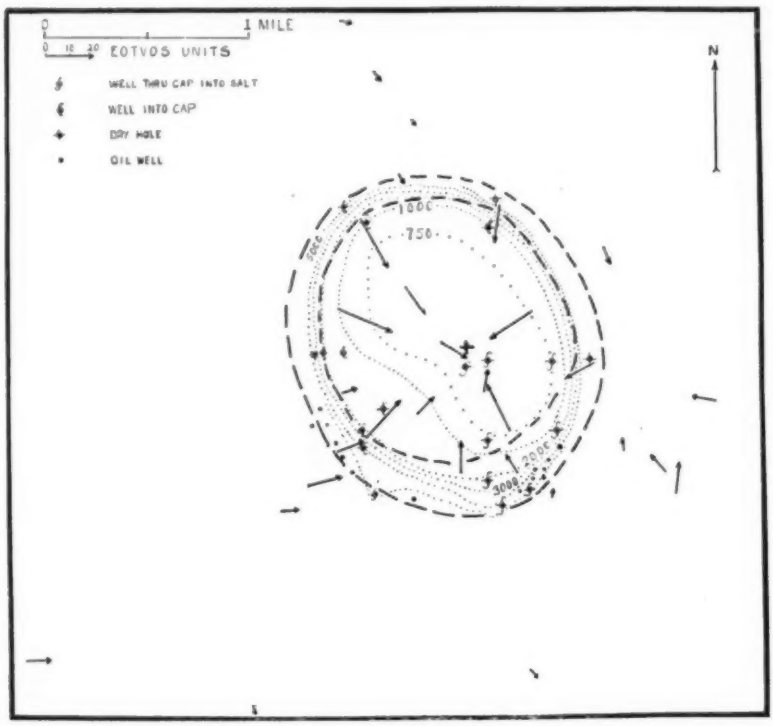

Fig. 4. Map of the Nash salt dome, Fort Bend and Brazoria Counties, Texas. (From Bulletin of the American Association of Petroleum Geologists.)

data and as yet has not been reached by the drill. The calculated form of approximately what the Esperson salt plug must be is shown in Fig. 6. An example of successful quantitative use of a torsion balance survey is shown in Fig. 7 which depicts a vertical cross section of the Hoskins Mound salt dome, one of the three most important sulphur deposits of the world. The observed gradient profile and the observed gradient arrows are shown above the section. Sulphur was being mined from the cap to the left of well *A*, but previously to the torsion balance survey, the declivity on the top of the cap between wells *A* and *B* was supposed to mark the right edge of the dome. The torsion balance survey was made to see whether or not the cap might extend

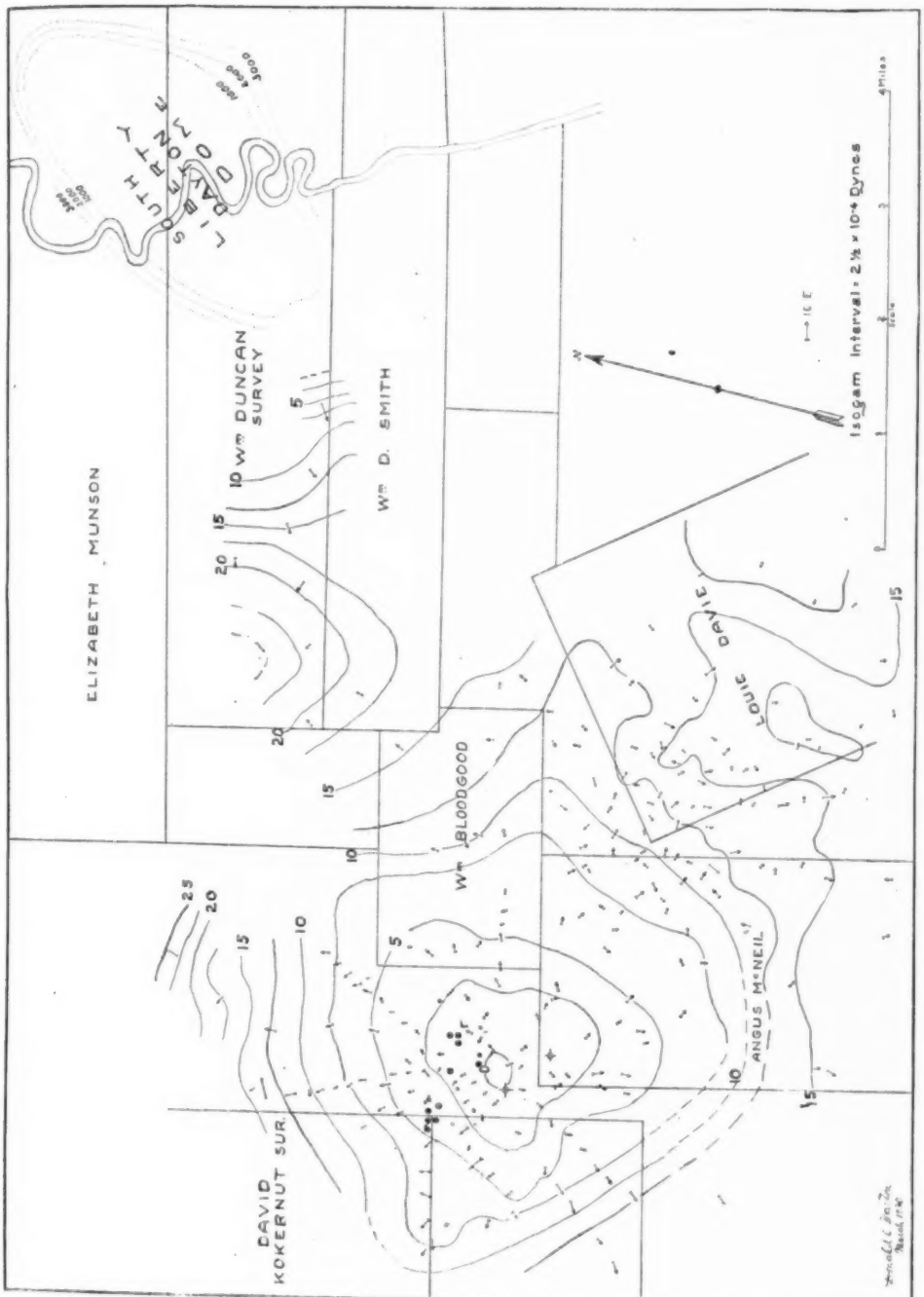

Fig. 5. Map of the Esperson salt dome, Liberty County, Texas. (From Bulletin of the American Association of Petroleum Geologists.)

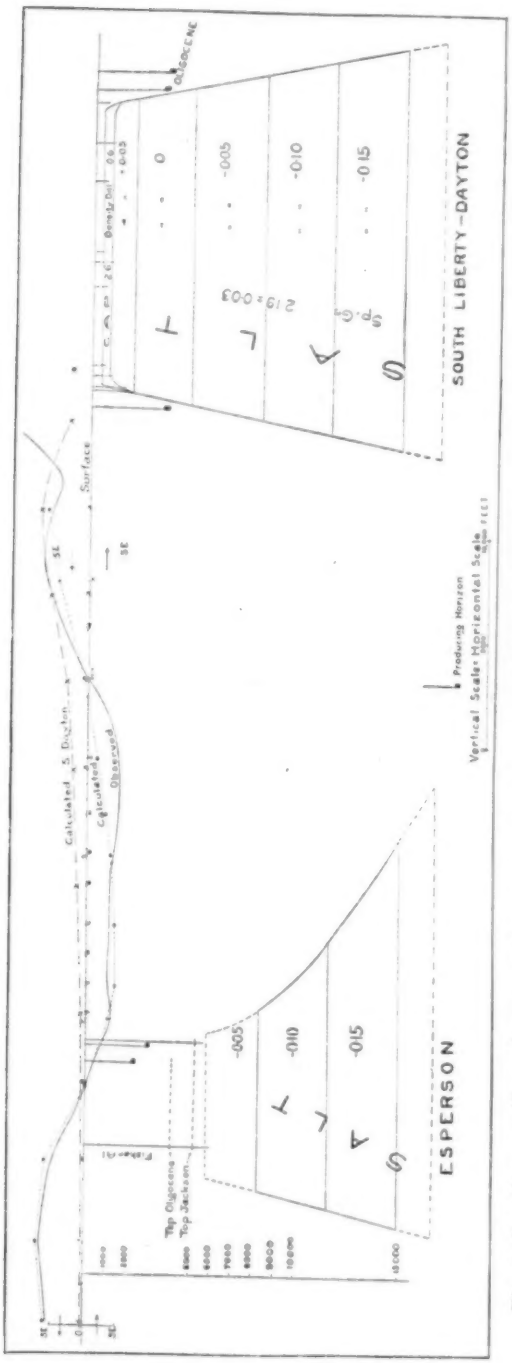

Fig. 6. Gradient profile and cross section across the Esperson and South Liberty-Dayton salt domes, Liberty County, Texas. (From Bulletin of the American Association of Petroleum Geologists.)

farther to the right. On the basis of calculations which were based on the torsion balance data, the cap was predicted to have the form depicted by the

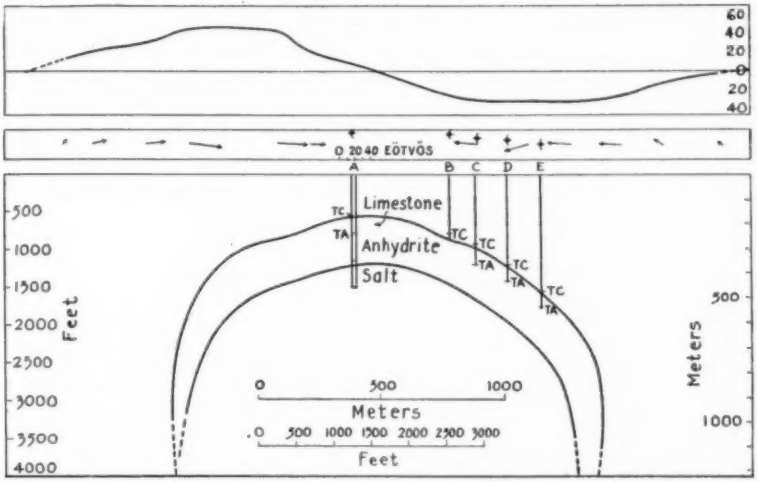

Fig. 7. Gradient arrows, gradient profile, and cross section across the Hoskins Mound salt dome, Brazoria County, Texas. (From "Geophysical Prospecting, 1929," American Institute of Mining and Metallurgical Engineers.)

solid lines. Wells *B*, *C*, *D*, and *E* were drilled subsequently. The position of the top of the cap in each well is shown by the cross line marked *T C*. Quanti-

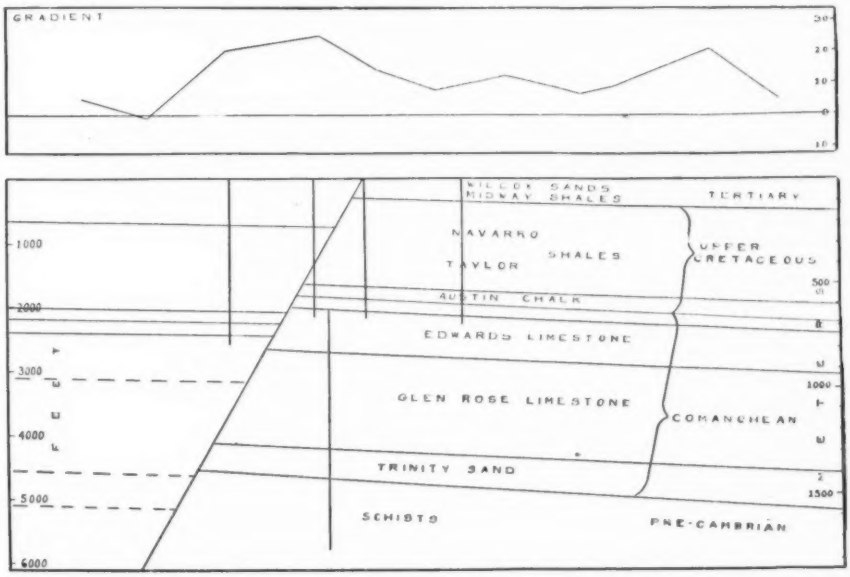

Fig. 8. Gradient profile and cross section of the Luling fault, Caldwell County, Texas. (From "Geophysical Prospecting, 1929," American Institute of Mining and Metallurgical Engineers.)

tative calculations with the torsion balance usually are not so accurate as those at Hoskins Mound. A gradient profile across the Luling fault is shown

in Fig. 8. The beds at the left have sunk relatively to those on the right and the relatively heavy Edwards limestone of the up-throw side is faulted against the lighter over-lying beds and produces a horizontal discontinuity of density which produces the two large gradient values immediately above the trace of the fault on the Edwards limestone. Above and below the Edwards limestone of the up-thrown side, the beds opposing each other across the fault have about the same density and, therefore, there is not enough contrast in density to produce much affect on the gradient. The gradient profile also shows the presence of a southeastward regional gradient (toward the right). That regional gradient mystified the writer when the survey was made, for the area lies not far southeast of the broad Llano-Burnet granite uplift and, theoretically, the basement should be sloping southeastward and should produce a northwesterly regional gradient. Subsequent drilling has shown that a deep structural trough intervenes between this area and the Llano-Burnet uplift and the basement in this area in general slopes northwestward. A southeasterly regional gradient, therefore, is expectable.

The Application of the Reflection Seismograph

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INTRODUCTION

THE seismograph has proven its ability in a great many instances accurately to delineate subsurface geologic structure. There are two general divisions of method—refraction and reflection. In the former, energy refracted from a buried high velocity stratum is utilized while in the latter reflected energy from the high velocity stratum is used to determine its depth below the surface. In either case the initial energy is derived from a charge of dynamite exploded near the surface of the ground. The time of explosion and the motion of the ground at some point, either near to or distant from the scene of the explosion, is recorded on photographic paper. Suitable timing lines are also photographed on the paper so that the traveling time of the different events arriving at the recording position from the generating point may be determined with the necessary degree of accuracy. The longitudinal wave is used to the exclusion of other types.

TYPES OF GEOLOGIC STRUCTURE

The four general types of geologic structure responsible for the accumulation of oil will now be described. Oil is found in porous, pervious strata such as sands, sandstones and limestones. The oil is separated by gravitational means from the water which is usually present. This and the trapping of the oil in its reservoir are accomplished in one of the several ways now to be described, or minor variations of them, in which the pervious reservoir rock is sealed by an impervious shale or limestone.

SALT DOME STRUCTURE

In the gulf coastal plain of Texas and Louisiana as well as in the large geologic basin of East Texas, salt domes are found. These are large plugs of almost pure crystalline salt which have been thrust upward into the softer sediments. In so doing they have formed traps for oil in these sediments as shown in Fig. 1. The source of these salt plugs has not been determined and suffice to say that this source is at least several miles deep. In most cases the presence of these domes is not apparent at the surface of the ground.

ANTICLINAL STRUCTURE

This type is the most common trap for oil and comprises subsurface domal formation in the strata as shown in Fig. 2. Sometimes this doming of the subsurface strata is reflected in the strata outcropping at the surface. In this

case the presence of the subsurface structure may be predicted by surface geological exploration. Often such structure is not reflected at the surface, in which case a geophysical method or the drill is employed.

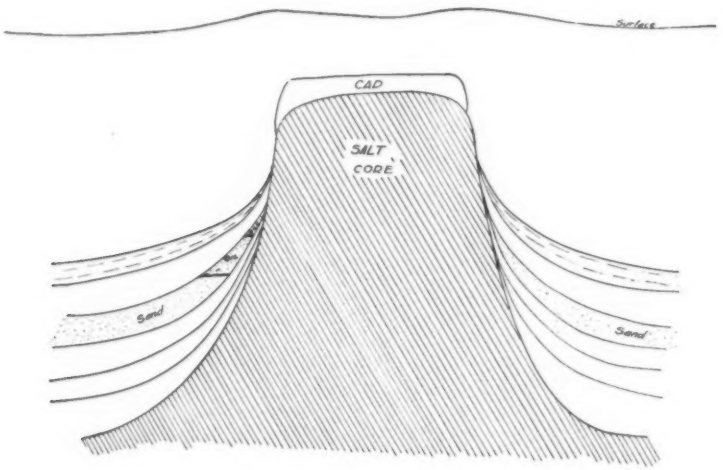


Fig. 1. Salt dome type of structure.

Faulted Structure

In some cases strains are set up in the earth which, on being relieved, cause whole sections of the earth to break and slide past each other. As a

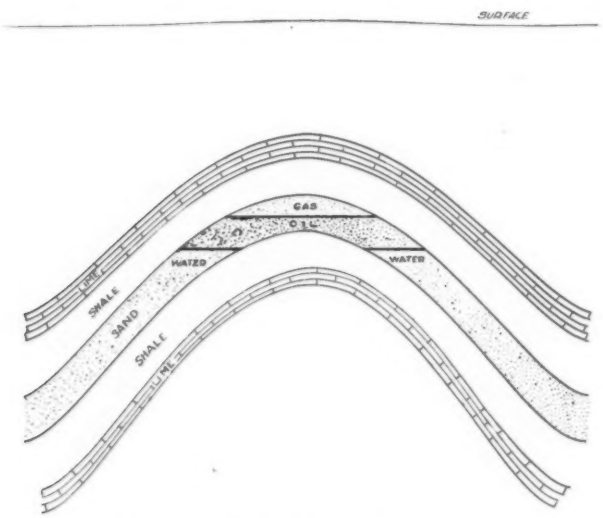


Fig. 2. Anticlinal type of structure.

result, oil may be separated and trapped as shown in Fig. 3. The Mexia-Powell fault line fields in Texas are the outstanding example of this type of structure. Such faults may often be detected by a study of surface geology

but in general the seismograph may contribute greatly to the location of a possible field in such a faulted area.

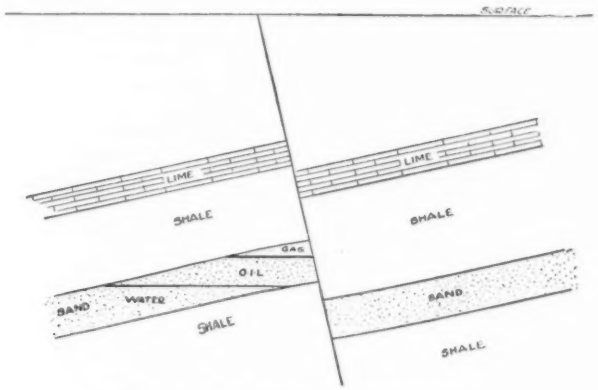


Fig. 3. Faulted type of structure.

Shore Line Structures

In this category are included not only true shore line structures but also all types resulting from change of sedimentation (as regards permeability) such as sand lens and old river channel deposits. Fig. 4 illustrates the general

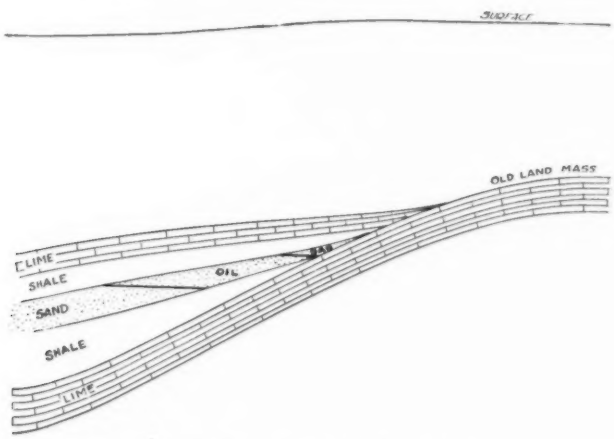


Fig. 4. Shore line type of structure.

case. Such fields usually give no superficial evidence of their existence. Only in very limited cases may the seismograph be of any assistance.

Shallow Salt Domes

The seismograph was first commercially used in the gulf coast of Texas in 1924 to locate salt domes. As the velocity of sound in this salt plug is high compared to the surrounding sediments (16,000 ft. per sec. compared to about

6000 ft. per sec. for the sediments) the seismograph had no difficulty locating them when the top of the plug came to within a few thousand feet of the surface. A shallow salt dome of average size, a mile or so in diameter, resulted in time anomalies from normal of 0.5 or 0.6 of a second. As the accuracy of the first seismographs used was of the order of a few hundredths of a second, no difficulty was experienced in detecting the presence of such a buried salt dome. The recording instruments were usually placed less than three miles from the shot point. Dynamite charges of the order of 100 pounds were found sufficient. The distance between the shot point and the recorders was determined with sufficient accuracy by means of the sound wave traveling through the air from the shot point to the recorders. The time of explosion of the charge was transmitted to the recording station by means of radio. Thus, by measuring the time of transmission of the wave through the ground, it was possible to determine the presence of a salt dome beneath the surface. As the velocity of an elastic wave in the earth increases with depth below the

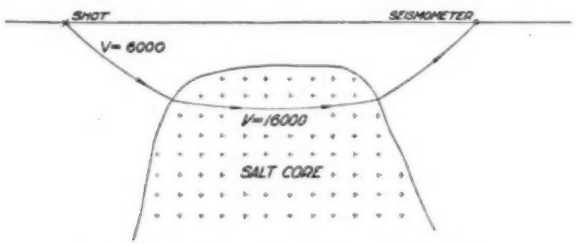


Fig. 5. Refraction path through salt dome.

surface due to the increase of elasticity with increase of overburden (the density changes very little) the shortest time path between shot and recorder points will be curved concave upward. In exploring for salt domes the arrival time of only this first disturbance is determined. The effect of the presence of the salt dome may be readily deduced from Fig. 5.

Deep Salt Domes

By moving the recorders six to eight miles from the shot it was possible to explore for salt domes to a depth of 4000 to 5000 feet. As the time anomalies resulting from the presence of such deep domes were 0.1 sec. or less it was necessary to increase the accuracy of timing to at least 0.01 sec. and to accurately survey the distance between shot and recorder. Charges as large as 1000 pounds were required. A large number of such deep domes have been located with the seismograph.

Structure Determination by Refraction Method

The refraction method has been applied to delineating subsurface structure in the case of both the anticlinal and faulted type. As this method has so far made no progress in the way of using any but the first arrival of energy at the recorders, it is necessary to separate the recorders a considerable distance from the shot in order to penetrate to any great depth. Also, it is neces-

sary to have a considerable thickness of the high velocity medium to obtain enough energy return from it. The comparatively large charges necessary combined with the large distances between shot and recorders and the consequent slowness of operation make the method expensive. It does, however, have the advantage of identifying the refracting horizon by its velocity. This velocity is determined by placing a number of recorders on a line of profile at increasing distances from the shot point. By means of such a profile and a knowledge of variations of velocity of the overlying sediments with depth it is possible to determine the depth to the refracting strata. Fig. 6 shows the path traversed by a refraction of the type we have been discussing. The velocity in both mediums is assumed to increase linearly with depth as shown. In Fig. 6 V_0 is the surface velocity and V_1 the average velocity from the surface

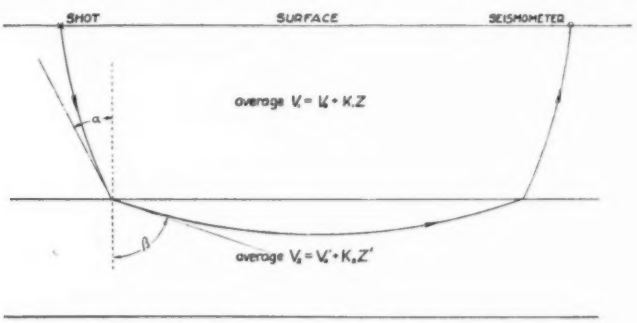


Fig. 6. Refraction path for structure determination.

to a point at any depth, Z, below the surface in the upper formation. Also in this figure V_0' is the velocity at the top of the lower medium and is assumed to be larger than the velocity at the base of the overlying medium and V_2 is the average velocity from the top of this lower medium to a point at a depth Z', below this top. K_1 and K_2 are constants.

Reflections

The inception of the reflection method on a practical operating basis dates from 1928. This method has proven itself more accurate and less expensive than the refraction seismograph. The accuracy of depths determined from reflection records may conservatively be stated to be 0.5 percent when the records are of good quality and the correlations are not too difficult. The average charge of dynamite is less than two pounds. The difficulty of correlating records from different shot positions will depend on the complexity of the geologic column. Large shale sections overlying hard limestone members will enhance the ease of correlations. When the section is composed of a multiplicity of limestone members with but small sections of shale or sand between or when the limestone members are sandy and not well defined, obviously the correlation of reflection events from one position to another will be difficult just as the correlation of such a stratigraphy would be difficult even from a physical examination of well samples. Correlation difficulties are usually the result of too many reflection events appearing on the record

rather than too few. The ideal case from the geophysical viewpoint would be to have a single hard reflecting horizon buried in soft shale which, of course, would give one outstanding reflection. However, from a geological standpoint it is often advisable to have some knowledge of the age of the folding. By determining the depths to several horizons of different geologic age and observing the changing intervals between these horizons, it is possible not only to determine the folding in or near the oil bearing strata but also to ascertain the geologic time during which the folding occurred. This last factor of timeliness of folding may in some areas have as much bearing on oil accumulation as the actual folding of the oil bearing strata. Therefore, it may be said that the preferred case would be several good reflecting horizons of different geologic age with fairly large intervals of soft rock between the hard reflecting members.

The character of a closely occurring group of reflections, the interval between more widely separated reflections and the determination of the slope of the reflecting strata, where it is sufficiently great, by observation of the time occurrence of a series of reflections secured from multiple recorders photographed simultaneously on the same record are the essential aids to correlation.

Velocity

The velocity of the earth materials may of course be determined from their density and elastic constants according to the well-known relations:

$$V_L = (I + 4/3K/D)^{1/2}$$
$$V_T = (K/D)^{1/2}.$$

Where V_L is the velocity of longitudinal waves, V_T that of transverse waves, I is the incompressibility, K the rigidity and D the density, all of which should best be determined *in situ*.

The velocity is, however, determined in practice by other methods. The best procedure is to lower a seismometer into a well and detonate explosive charges at the surface as the seismometer is held at different depths. Outside of the first thirty feet or so of soil, or weathered material, the velocity increases with depth and the average velocity between the surface and any depth Z, may in general be expressed by the simple linear function:

$$V = V_0 + KZ$$

Where V_0 is the surface velocity (neglecting the weathered layer) and K is a constant. In some cases where sufficiently large discontinuities occur in the section, it may be necessary to use more than one such function. It should be remembered that relative depths to the same formation at different points on the surface are more important than an absolute depth to that formation.

Having made one velocity determination by the above method it is usually sufficient to check the depth to the formation by means of reflections against depths determined from wells in the area being surveyed. As changes in velocity in a given area will be found usually to occur uniformly, a velocity

contour map of the area will permit its adjustment throughout the area. Such gradual, or regional, velocity variations will not seriously affect the accuracy of structure determination as these are of limited regional extent compared with the velocity variations.

The velocity to a given reflection marker may be determined approximately by placing a number of seismometers in profile at different distances from the shot point and plotting the resulting times squared against the distances squared. As one is a linear function of the other the slope of the resulting line will be the square of the velocity. As this value is determined from second order quantities, it will be quite approximate, unless a large amount of data is collected in this fashion. The method is of some use in areas where there is no information concerning the velocities.

The above determination of velocity excludes the surface weathered layer. The velocity of this layer (about 30 feet thick) is very low as a result of the action of percolating surface waters and it is therefore treated separately. Its thickness and the time consumed in it are determined by means of a small refraction shot. For example, the average velocity in this layer may be 3000 feet per second, whereas the velocity in the unweathered layer underneath is seldom less than 6000 feet per second. The velocity of the soil immediately at the surface is less than the velocity in air.

Angle of Reflection

In Fig. 7 are two reflection records showing reflections obtained at different distances from the shot point. Attention is called to the great similarity between the reflection events obtained at the two widely different spreads between shot and recorders. The charge of dynamite used in either case was the same, 0.5 pounds. It is, of course, desirable from an operating viewpoint to use the shortest distance possible. The optimum distance for all practical purposes is only remotely a function of the reflection angle. The choice of distance is primarily determined by the occurrence in the record of undesirable disturbances such as transverse and surface waves and refractions from shallow strata. The distance is so chosen that these unsought disturbances do not occur on the record at the time of the arrival of the reflection. When they do so occur the reflection event is obscured. Changing this distance offers a ready means of discriminating against such undesirable disturbances.

In a paper published in the Philosophical Magazine of July 1899 by C. G. Knott a complete exposition of the theory of the reflection of elastic waves at the interface of two rock mediums of different elastic constants, together with several numerical examples, is beautifully presented. According to the theoretical considerations of this paper the reflection efficiency of such an interface increases markedly beyond the critical angle and from the viewpoint of application, angles larger than the critical angle are desirable only when the problem involves the securing of reflections from the shallowest subsurface reflecting interface. When reflections are desired from a deeper interface, which is usually the case, the high efficiency of the shallower reflecting interfaces requires the use of smaller angles of reflection. Calculations based on

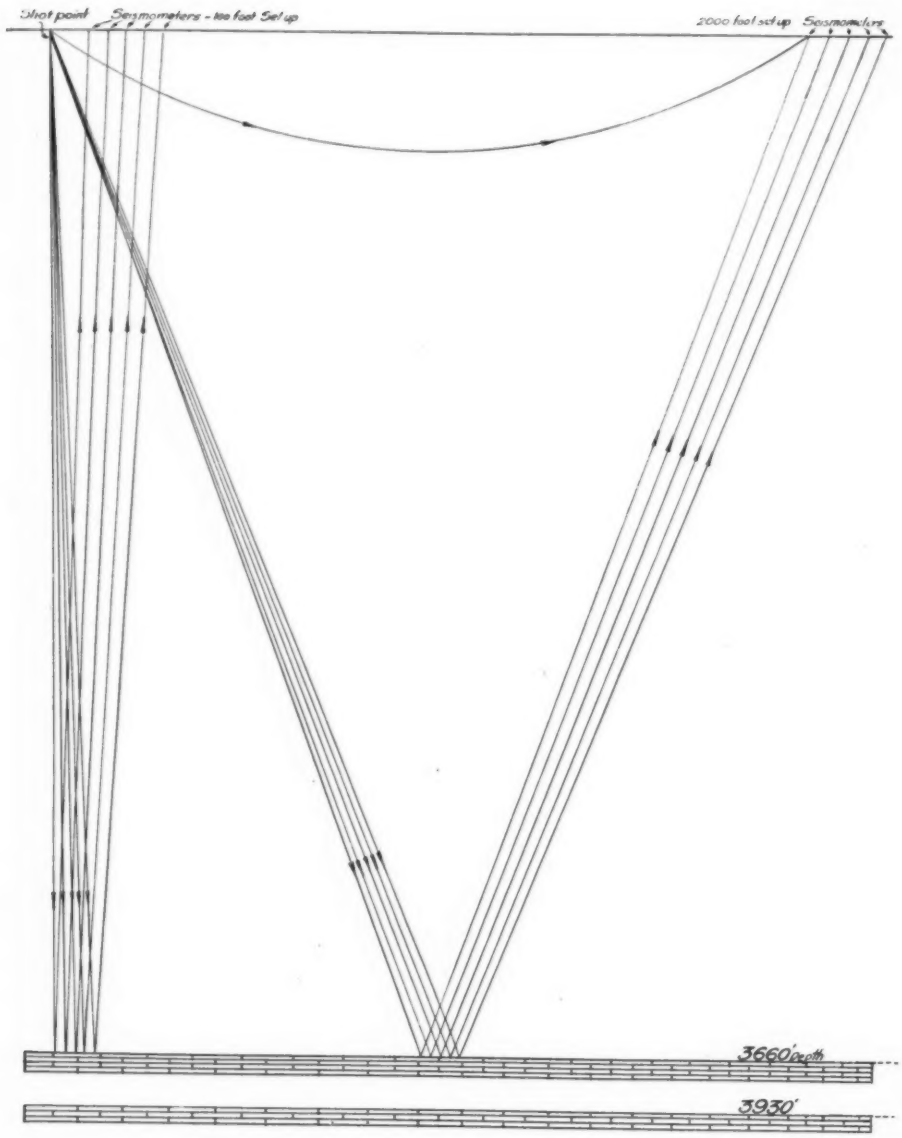
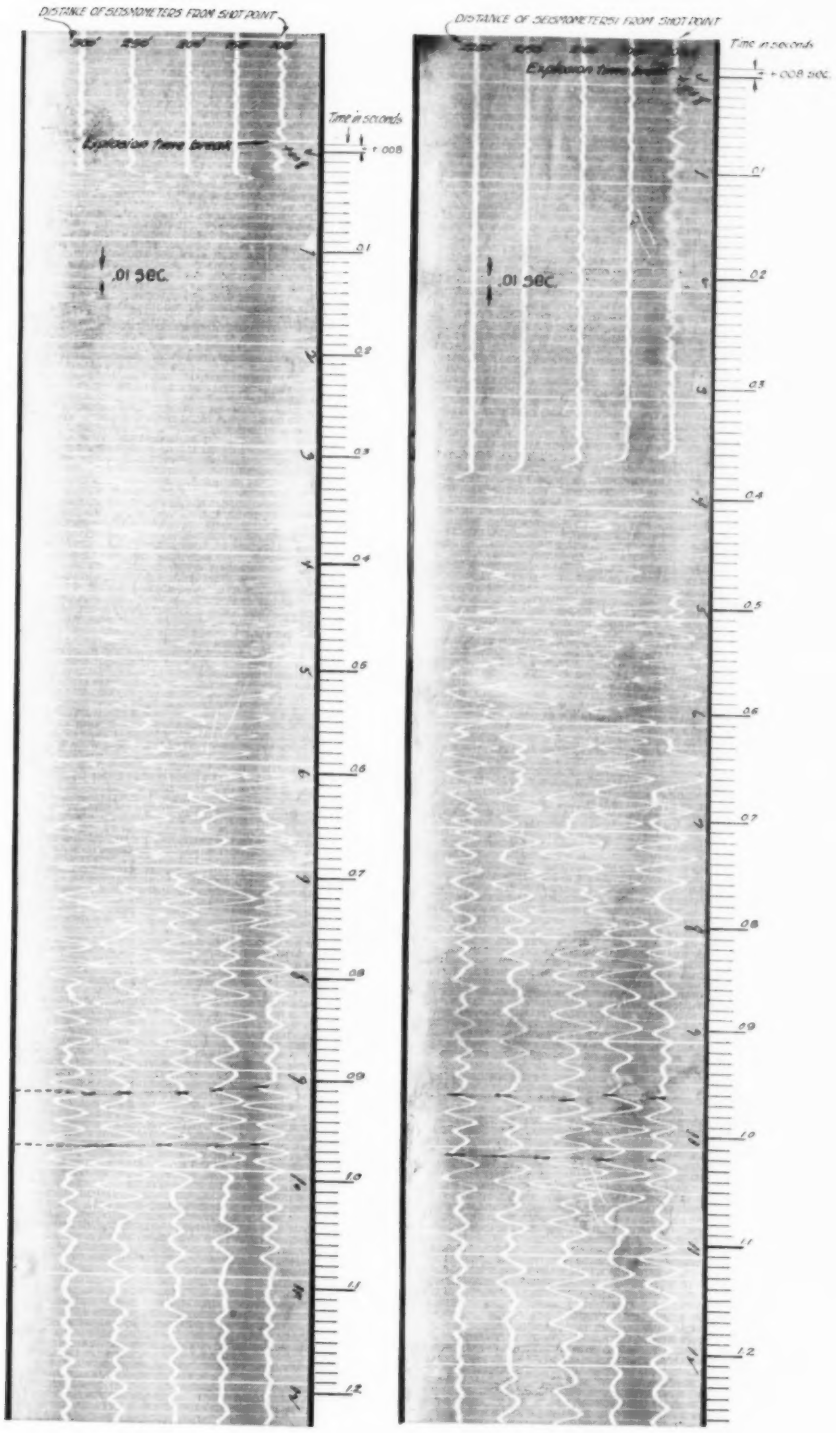
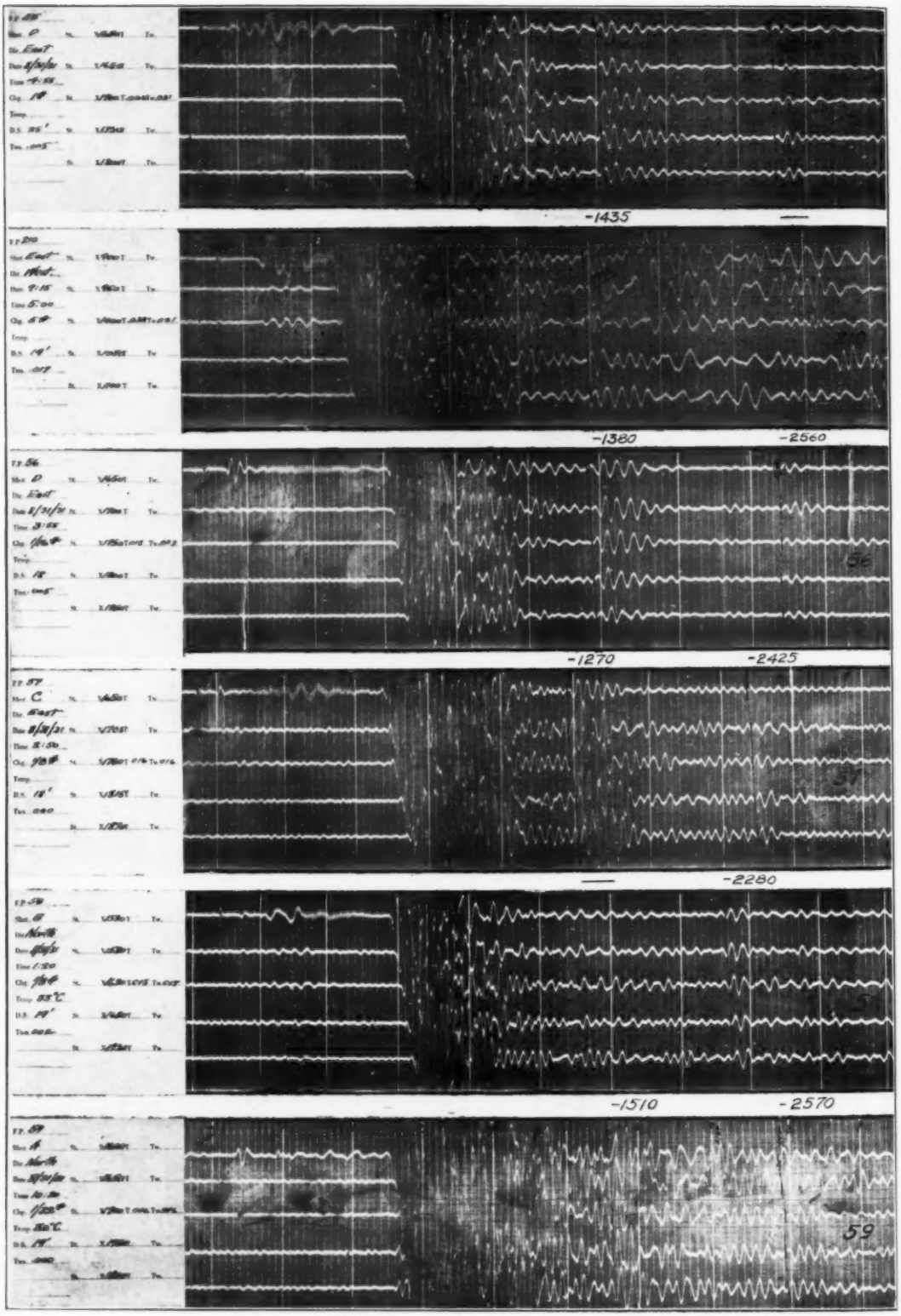


Fig. 7. Records showing variation of reflection angle. Bastrop County, Texas.


DISTANCE OF SEISMOMETERS FROM SHOT POINT
Time in seconds
Explosion Time Break
.01 SEC.
DISTANCE OF SEISMOMETERS FROM SHOT POINT
Time in seconds
Explosion Time Break
.01 SEC.


-1435
-1380
-2560
-1270
-2425
-2280
-1510
-2570

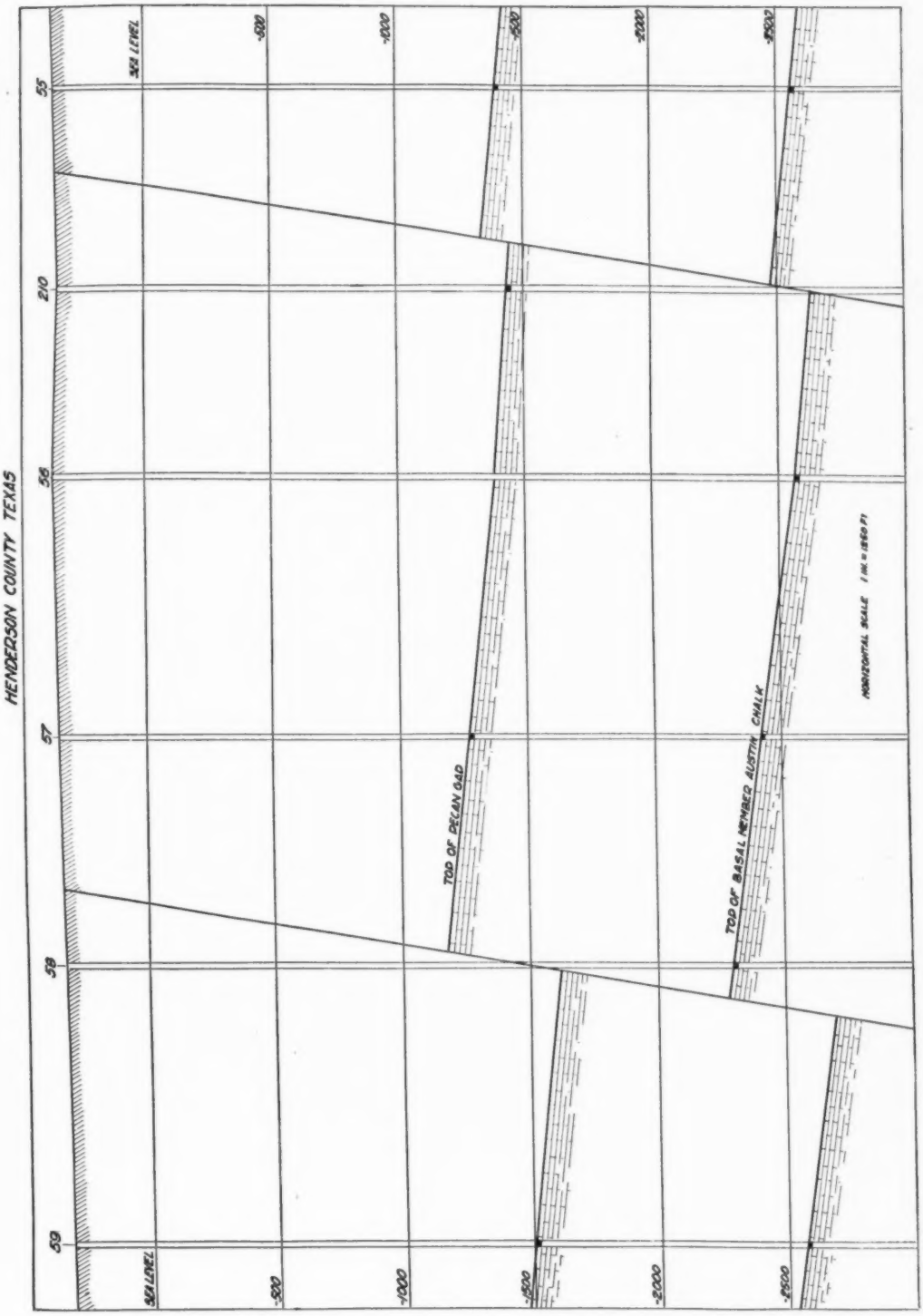


Fig. 8. Records and cross section of north extension of Mexia-Powell fault zone.

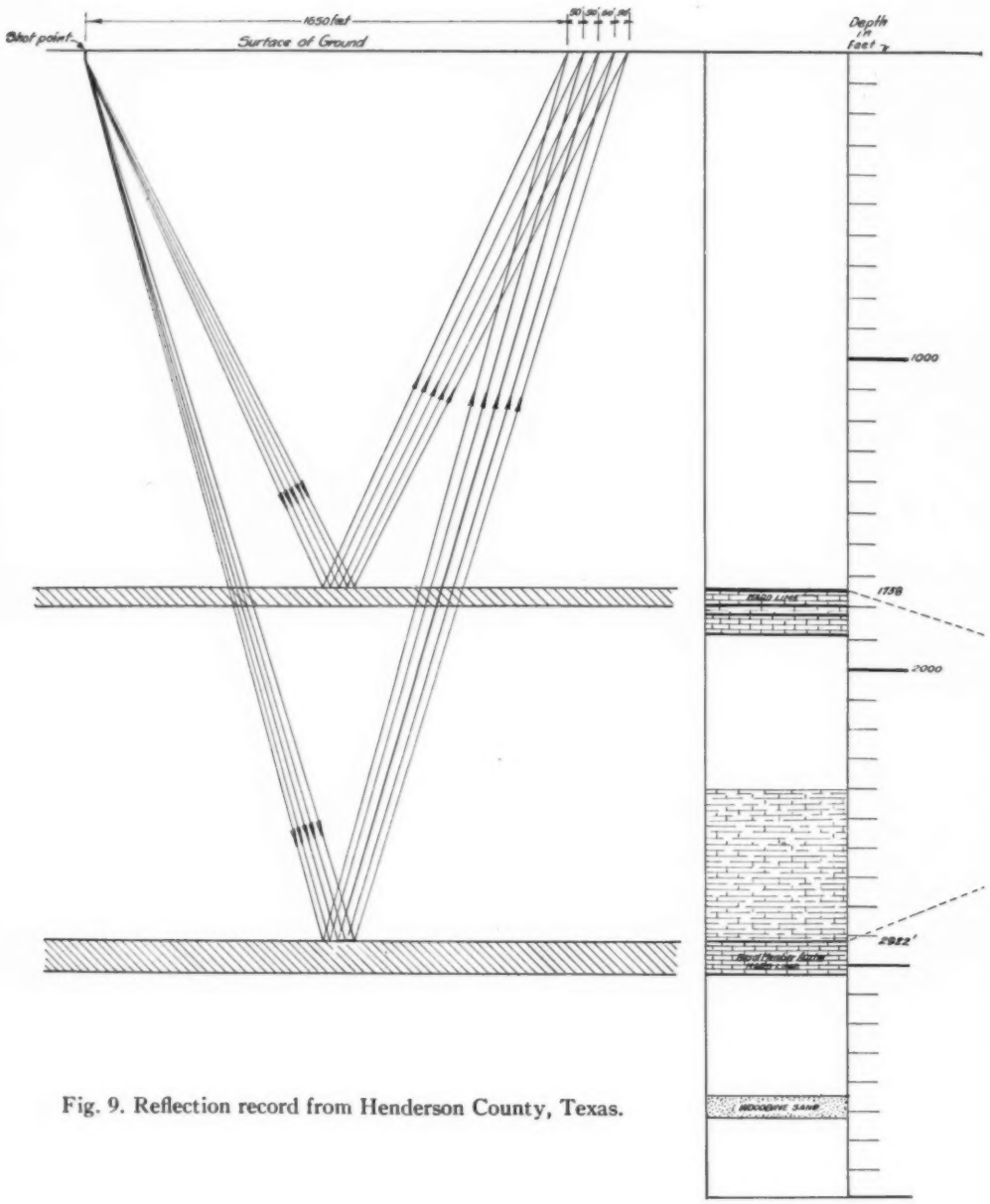


Fig. 9. Reflection record from Henderson County, Texas.

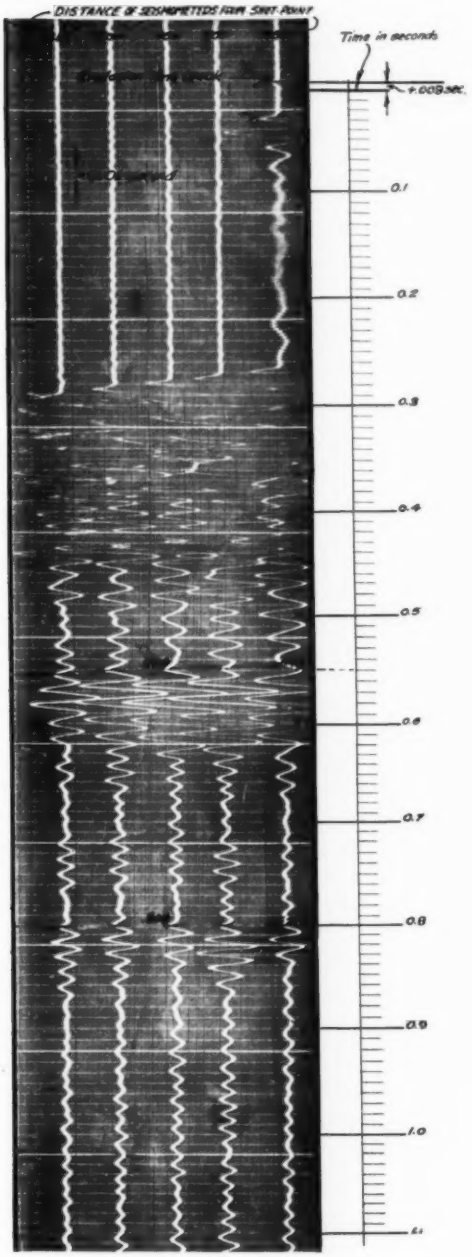

DISTANCE OF SEISMOMETERS FROM SHOT-POINT
Time in seconds
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Fig. 9.

Knott's formulas indicate that for the number of shallower reflecting horizons usually met with in practice, very small angles far removed from the critical angle, are desirable. The presence of undesirable disturbances from the shot point limits the use of the smallest angles. The optimum reflection angle from a consideration of the method presented in Knott's paper depends on the number and character of reflecting interfaces, and may be calculated for any case from the physical constants.

The fact that there are a number of shallow reflecting horizons, undoubtedly explains the equal energies of the reflections indicated in Fig. 7. The angle of reflection varies in this figure from 1° to 22°. The geologic section is fairly typical of the average encountered in practice.

Application

The accompanying cross section and records of Fig. 8 show clearly how a faulted area may be delineated by means of the seismograph.

Two dominant reflections were obtained throughout a large area in western Henderson and eastern Navarro counties in Texas just north of the Powell Oil field. These reflections were identified with the top of the Pecan Gap chalk and a hard basal member of the Austin chalk. These two members are shown on the cross section. The remainder of the section is composed mainly of shale and sand. The Woodbine sand, the producing sand in this area, lies 400 to 500 feet below the base of the Austin chalk. Attention is called to the presence of only one reflection in records 210 and 58. An inspection of the cross section explains the absence of the other two. In the case of record 210 the Austin Chalk reflection is missing, whereas in record 58 there is no Pecan Gap reflection due to the presence of the subsurface fault.

An inspection of the interval between these two reflections shows it to be nearly constant, which means that practically all of the faulting occurred after Pecan Gap age. This may be the reason that, although the necessary structural conditions for oil accumulation are present, no oil is found.

Fig. 9. shows a larger scale view of a record taken in this area. The paths of the reflected impulses are shown as straight lines though they are actually curved due to the fact that the velocity in the formation increases with depth. For the reflection angles used this curvature may be neglected. The time of the explosion is transmitted electrically and recorded as shown.

The instruments and technique of the reflection method have been improved greatly as regards sensitivity and the exclusion of undesirable disturbances. As a result there are few prospective oil bearing areas where it is not now possible to use the method to advantage.

ERRATUM

Dielectric Properties of Some Glycols

By A. H. WHITE AND S. O. MORGAN

PHYSICS **2**, 313 (1932).

On checking our calculations before returning the proof of our paper on "The Dielectric Properties of Some Glycols", which appeared in the May issue of Physics, an error in the order of magnitude of the $T\tau$ values in Table IV was discovered. As a result of this error the values of molecular radius for 2-methyl pentandiol 2.4 as given in Table IV are too large.

The simplest way of correcting this error appeared to be to omit Table IV and the last two paragraphs of the paper and to substitute for them another paragraph giving the correct radius. However, as published, the two paragraphs and the table were left intact and the paragraph intended to replace them merely added on. Table IV, the last paragraph on page 320 and the first on page 321 of our paper should have been omitted.

THE EDITOR'S COLUMN

Magneto-Optical Method of Chemical Analysis

PERHAPS the method to be described should be called the magneto-optical method of detecting the chemical elements rather than the title given. In its present development, it is of little value in making quantitative chemical analyses but does seem to be an extremely sensitive method of detecting the presence of a minute quantity of an element. By this method the isotopic composition, at least the number of isotopes, of an element may also be determined.

When plane polarized light is sent through isotropic transparent liquids in the direction of an applied magnetic field, the plane of polarization is rotated. This is known as the Faraday effect. The rotation produced in a given substance per unit length per gauss for a given wave-length is known as Verdet's constant. The rotation is proportional to the field strength and the length of path in the magnetic field. It also depends upon the wave-length of the light.

Beams and Allison[1] and Allison[2] determined the time lag between the application of the magnetic field and the appearance of the Faraday effect. Their methods determined the difference between the lag in carbon disulphide (which has a relatively high Verdet constant) and other liquids. The differential lag was of the order of 10^{-9} sec., depending on the wave-length of light used.

In the experimental arrangement monochromatic (filtered) light is polarized by one nicol prism, sent through two glass cells in which liquids may be placed and then through a second nicol prism to the eye of the observer. The two glass cells are spaced some distance apart and are movable in the direction of their axes parallel to the light rays. About the cells are two solenoids which are supplied by current from the same condenser. This condenser is charged to a high potential, then discharged through a spark gap and a circuit which contains the solenoids in parallel. The solenoids are wound so that opposing magnetic fields are produced in them. The leads to the solenoids are arranged so that the length of path of the electrical circuit to one could be made the same, longer or shorter than the path to the other.

Observations are carried out in the following manner. The glass cells containing the liquid are removed and the two nicols set for extinction. Then the cells with the same liquid (CS_2) in each are placed in the solenoids and the length of path of the electrical circuit adjusted so that when the pulsating currents are passed through the solenoids the light from the source is extinguished by the two nicols. This extinction is presumedly obtained when the magnetic field of the second solenoid lags behind that in the first by a time equal to that required for light to travel from one cell to the next. The rotation produced in one cell is therefore annulled by that in the other. Their magnitudes are equal and the rotations are properly timed to give a minimum (in this case zero) light intensity to the eye of the observer. Then the carbon disulphide is removed from one cell and another liquid placed in it. By changing the length of the electrical circuit to the solenoid about this cell, a condition in which the light intensity is again a minimum is found. Dividing the increase (or decrease) in the length of the electrical circuit by the velocity of light gives the lag of the rotation of the plane of polarization in a given substance behind that in CS_2. Because of differences in Verdet constants, complete extinction is not obtained when two different liquids are used. The light intensity minima are sometimes rather difficult to observe. Attempts have been made to use a photoelectric cell to replace the eye but these have not been very successful.

The results obtained with a number of inorganic acids and salts have been published by Allison and his associates.[3] These indicate

[1] Beams and Allison, Phys. Rev. **29,** 161 (1927).

[2] Allison, Phys. Rev. **30,** 60 (1927).

[3] Jour. of Am. Chem. Soc. **52,** 3796 (1930); Ind. and Eng. Chem. (Anal. Ed) **4,** 9 (1932).

that multiple, rather closely spaced, minima may be observed with one salt solution. For example, with $MgCl_2$, Mg $(NO_3)_2$ or $MgSO_4$ in the cell, three minima are observed. In general it appears that the number of minima is equal to the number of isotopes of the metallic element. With this observation as a rule, new isotopes have been reported. Copper is thus found to have three isotopes.[4] The order in which the minima appear depends on the atomic weight of the individual isotopes. In this way the third isotope of copper is assigned an atomic weight less than 63 but the exact value can not be given. When the acids, HCl, HNO_3, H_2SO_4 were used two minima were observed. It is to be noted that these observations were made before the two isotopes of hydrogen were detected spectrographically or by means of the mass spectrograph. In a paper received May 13, 1930 and published in the October, 1930 issue of Journal of the American Chemical Society, Allison and Murphy state "Hydrochloric, nitric and sulfuric acids each produce two minima for which we are unable to account." Later the two minima were detected with water alone. The number of minima does not seem to depend on the negative radical with which the metal is combined.

Readings taken on various series of nitrates, chlorides, sulphates and hydroxides yield smooth curves when the differential time lags are plotted against the chemical equivalent. The greater the chemical equivalent of the metallic element, the smaller the time lag, in many cases the time lag is less than that for CS_2. Metals with two valences appear at two points in the curve for a given acid radical. In this way the detection of elements having the atomic weights and valences that are attributed to elements No. 85 and No. 87 have been reported.[5] Recently Allison and Goslin announced the detection of the transformation product of potassium. Assuming that one isotope (41) of K emits a beta-particle, the resulting product would be an isotope of Ca having an atomic weight 41. A scale reading of an element between Ca^{40} and Ca^{44} has been found in calcium salt solutions.[6]

The method is extremely sensitive. Concentrations of one part in 10^7 of water can be detected. Higher concentrations, however, give practically the same indications so that the method can not now be used as a satisfactory method of exact quantitative determination. Temperature changes have little or no effect on the location of the minima. The presence of two or more compounds causes no interference. Since the readings depend on the compound rather than metallic elements alone, the presence of several compounds of a single element may be determined. This method has a distinct advantage for many types of work in that a small amount of a compound may be used and that it is not altered in the process of analysis. It is reported to be very successful in analysis of the rare earths, a difficult job ordinarily.

In the above a rather detailed description of the apparatus has been given because the question as to just what is measured has been raised. If one calculates the results to be expected from such an apparatus, he would very likely be discouraged from ever trying the experiment. To obtain a pulse of current with a wave front steep enough to yield time lag readings as short as reported here seems out of question with apparatus as simple as that actually used. And what is the action when two or more compounds are present and two or more minima are observed? Each element, in fact each isotope, seems to produce its own rotation and at a different time than any other. It seems a theory would need to make the time of rotation dependent on e/m of the metallic radical and on the nonmetallic radical present.

One may ask whether it really is a time lag that is measured or is it some other, possibly an electromagnetic factor, that gives different scale readings. The fact that similar results are obtained when the cells are moved farther apart or closer keeping the electrical paths constant in length, indicates that the time factor is the essential one. The change in the light path is found to be slightly longer than the corresponding change in the length of the electrical circuit. Granting the assumptions made, this experiment gives a means of measuring the velocity of a pulse in an electrical circuit. The velocity of the pulse in the circuit was found to be about 97% of the velocity of light. Allison and Condon in a recent Letter to the Editor in the Physical Re-

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[4] Phys. Rev. **40,** 16 (1932).

[5] Phys. Rev. **35,** 286 (1930); Phys. Rev. **37,** 1178 (1931).

[6] Phys. Rev. **40,** 1015 (1932).

view[7] describe an experiment which supports the time lag theory. A solution of a mixture of compounds having both positive and negative Verdet constants is made up such that no rotations can be observed with an applied *steady* field of 2000 gauss. This solution is then placed in one cell of the apparatus, the other cell being empty. With no applied magnetic field, the two nicol prisms were set for the threshold of visibility. When the transient field was applied a definite increase in the brightness of the field was observed. This result can be interpreted as a lag in one rotation compared to the other, say the positive compared to the negative. For a brief interval then during the current pulse in the solenoid, the rotations are not compensated and more light is transmitted.

No work is reported on the analysis of organic compounds.

J. W. BUCHTA

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[7] Phys. Rev. **40**, 1021 (1932).